TMT Design and Cophasing

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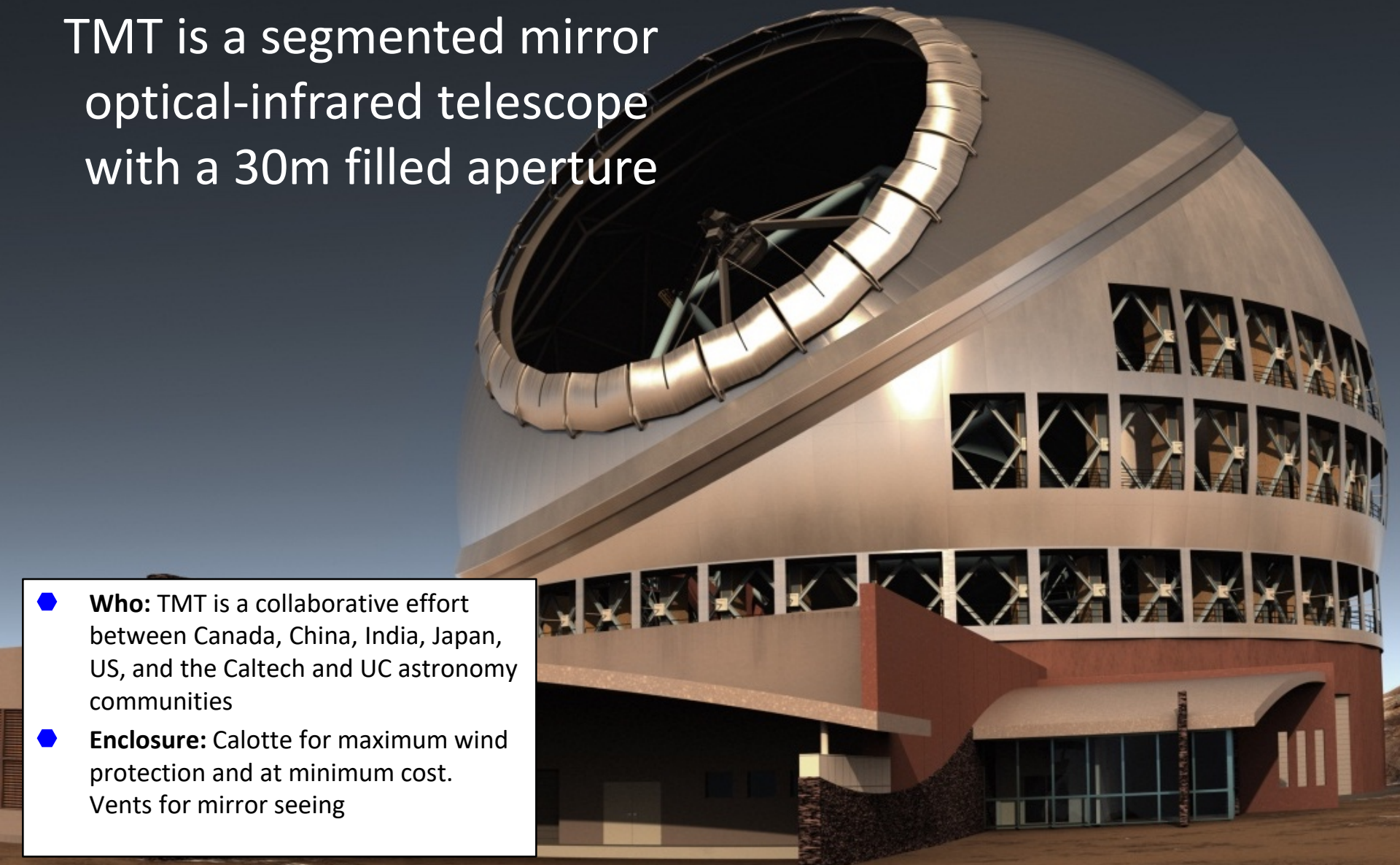
Outline

- Overview of TMT:
  - Telescope
  - Primary mirror control system
  - Alignment and Phasing System
- Phasing segmented telescopes
  - Basic description
  - Narrow band phasing – capture range +/- $\lambda/4$
  - Coherence phasing – capture range >> +/- $\lambda/4$
- Predicted impact of telescope aberrations on high-contrast imaging

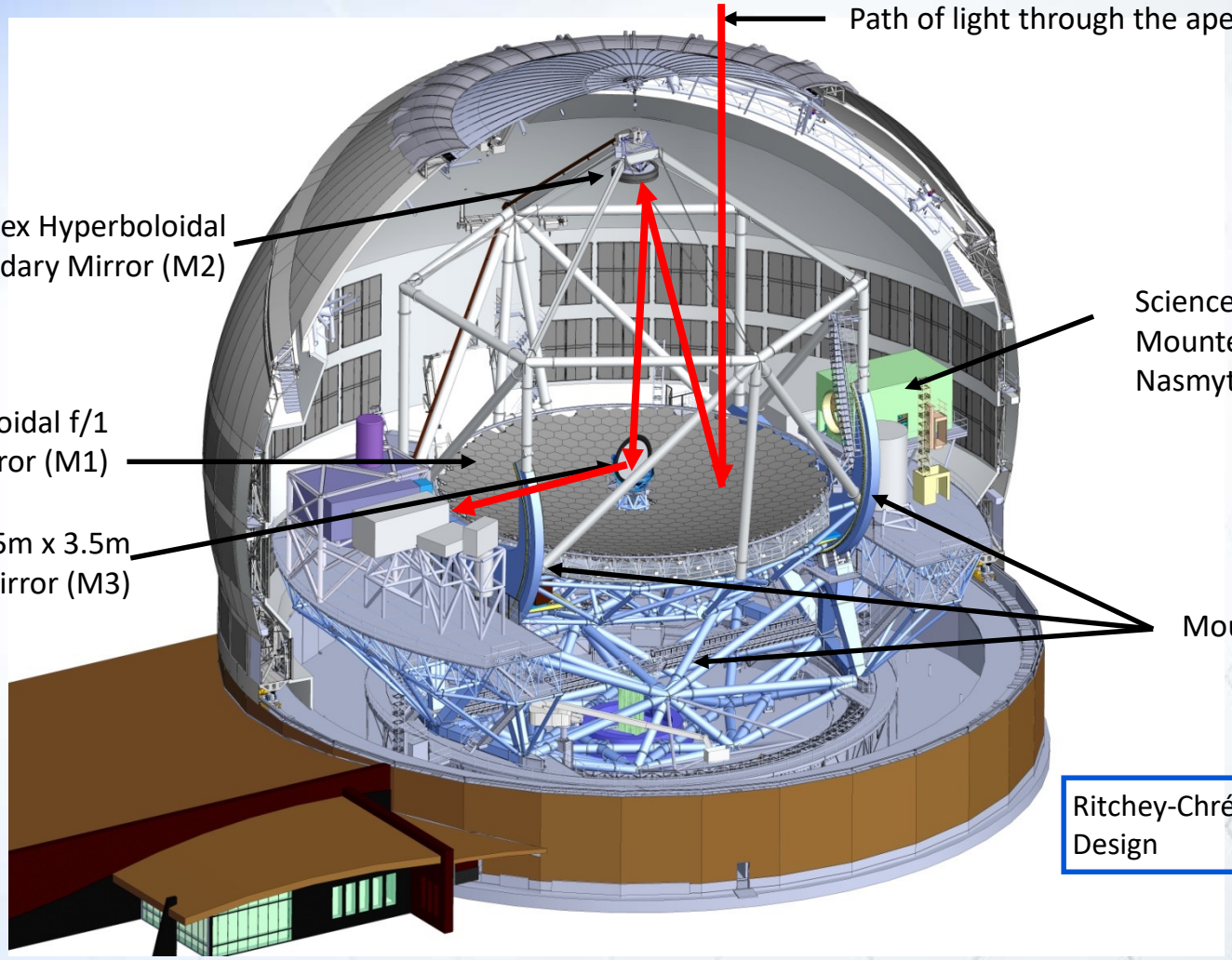
Introduction to the TMT Design

TMT is a segmented mirror optical-infrared telescope with a 30m filled aperture



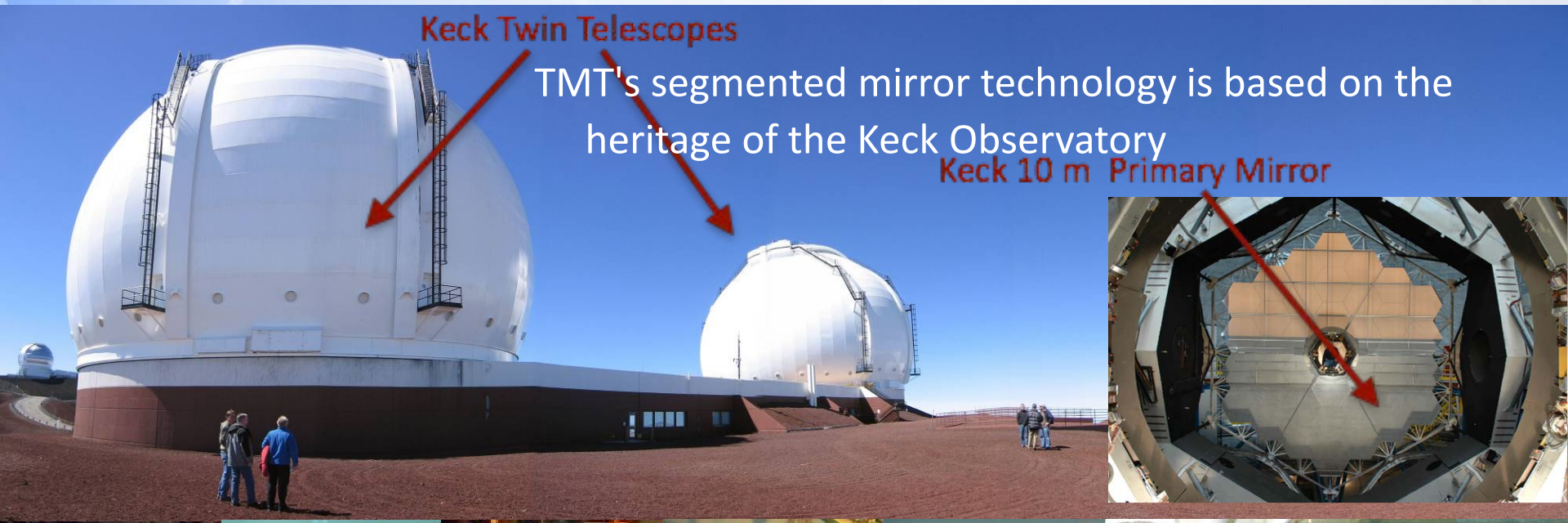
- **Who:** TMT is a collaborative effort between Canada, China, India, Japan, US, and the Caltech and UC astronomy communities
- **Enclosure:** Calotte for maximum wind protection and at minimum cost. Vents for mirror seeing

TMT Telescope Concept Overview



Ritchey-Chrétien Optical Design

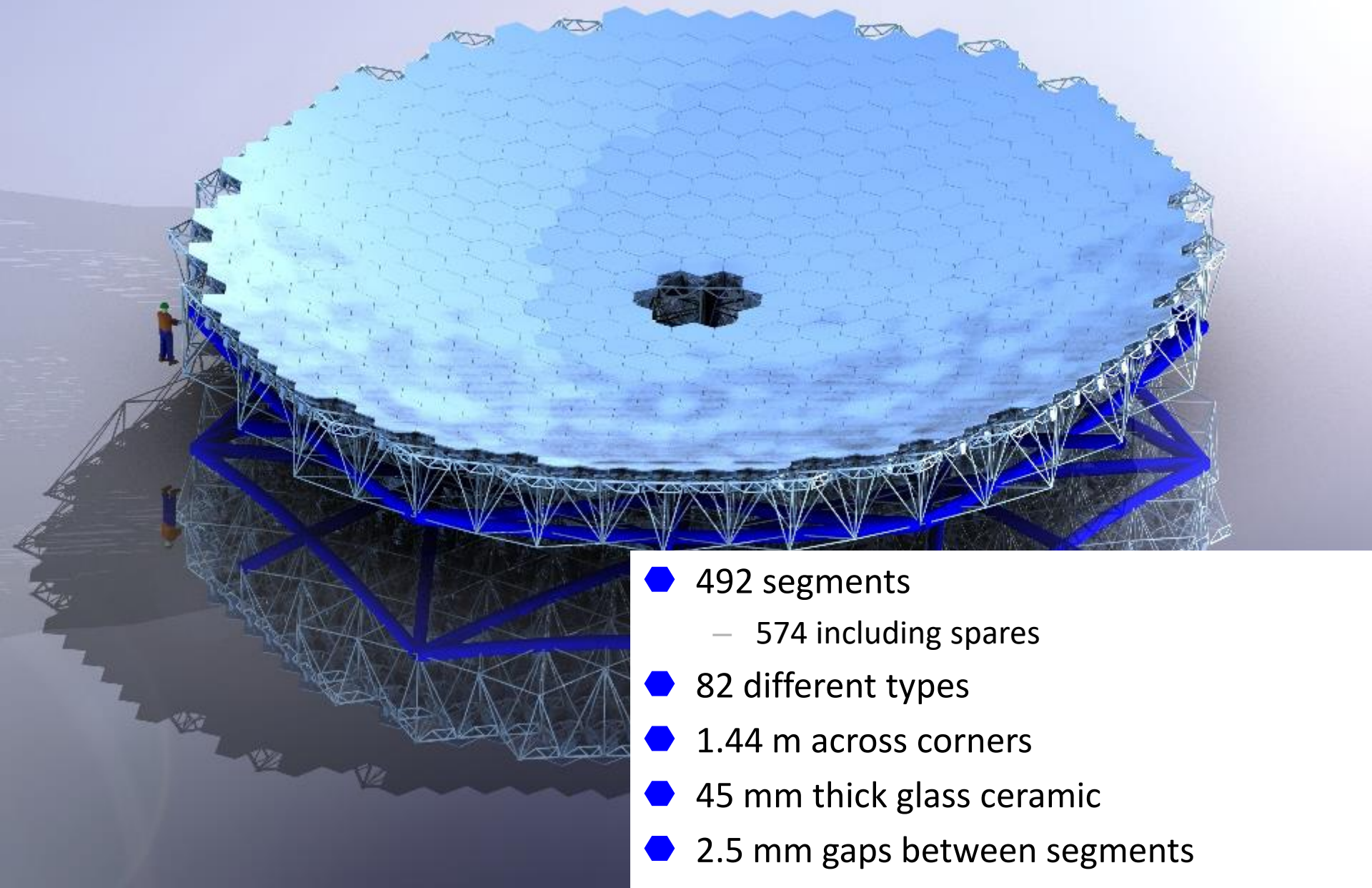
Design Heritage of TMT



TMT's segmented mirror technology is based on the heritage of the Keck Observatory

Fabr | Suppor | Warping h | Har | Edge senso | Alignment & phasing

TMT Primary Mirror (M1)



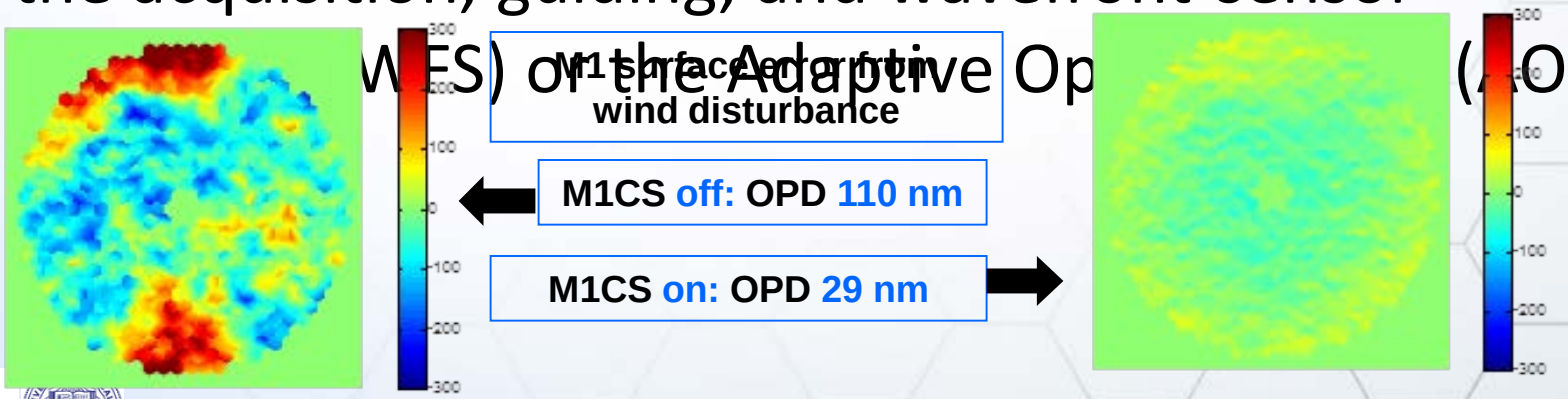
- 492 segments
  - 574 including spares
- 82 different types
- 1.44 m across corners
- 45 mm thick glass ceramic
- 2.5 mm gaps between segments

Primary Mirror Control System (M1CS)

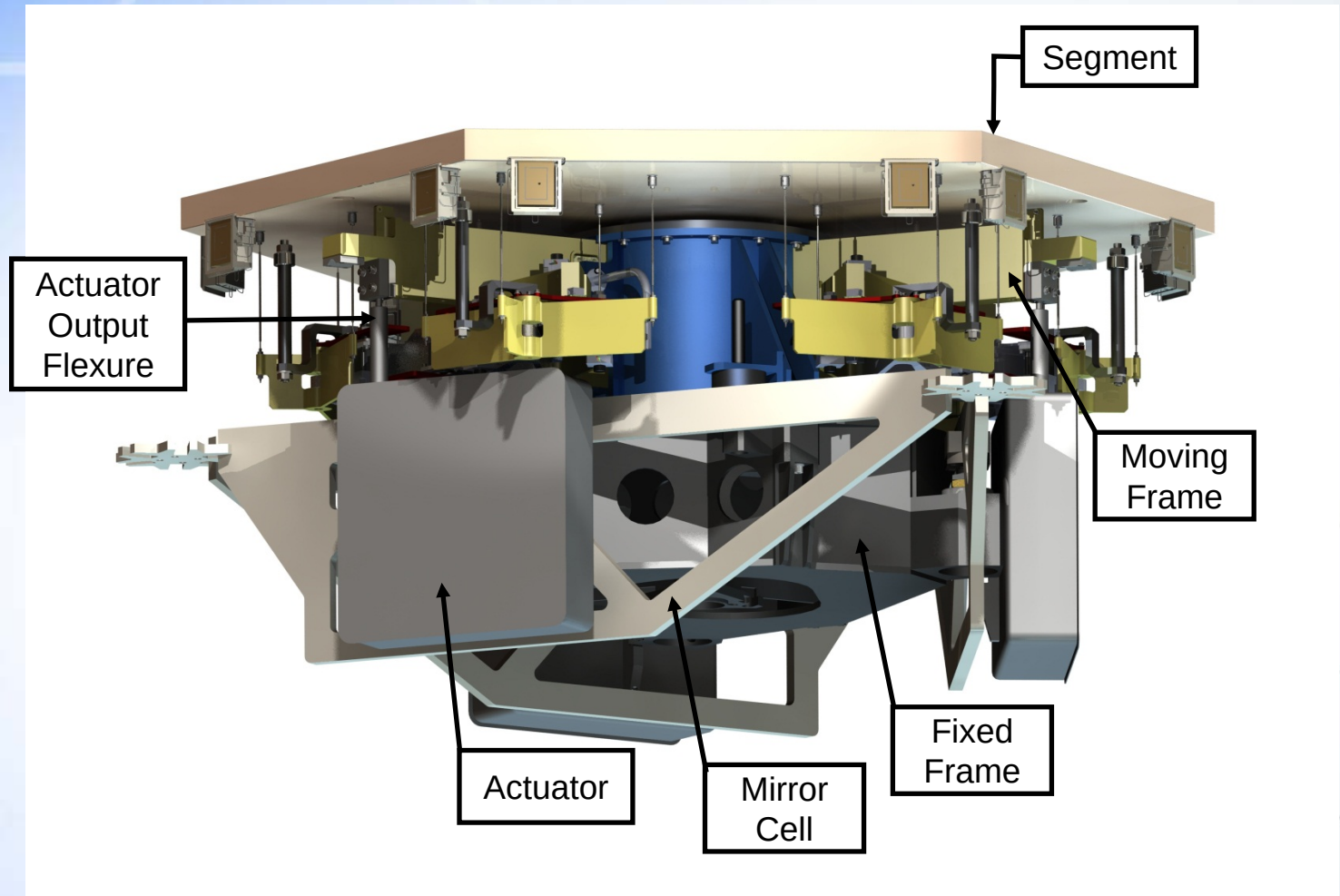
- Measures the shape of M1 using segment edge sensors
- Controls the shape of M1 using segment rigid-body actuators
- Maintains the shape of M1 in the presence of disturbances
  - Changing elevation angle
  - Wind
  - Vibration sources
  - Temperature

M1CS, Continued

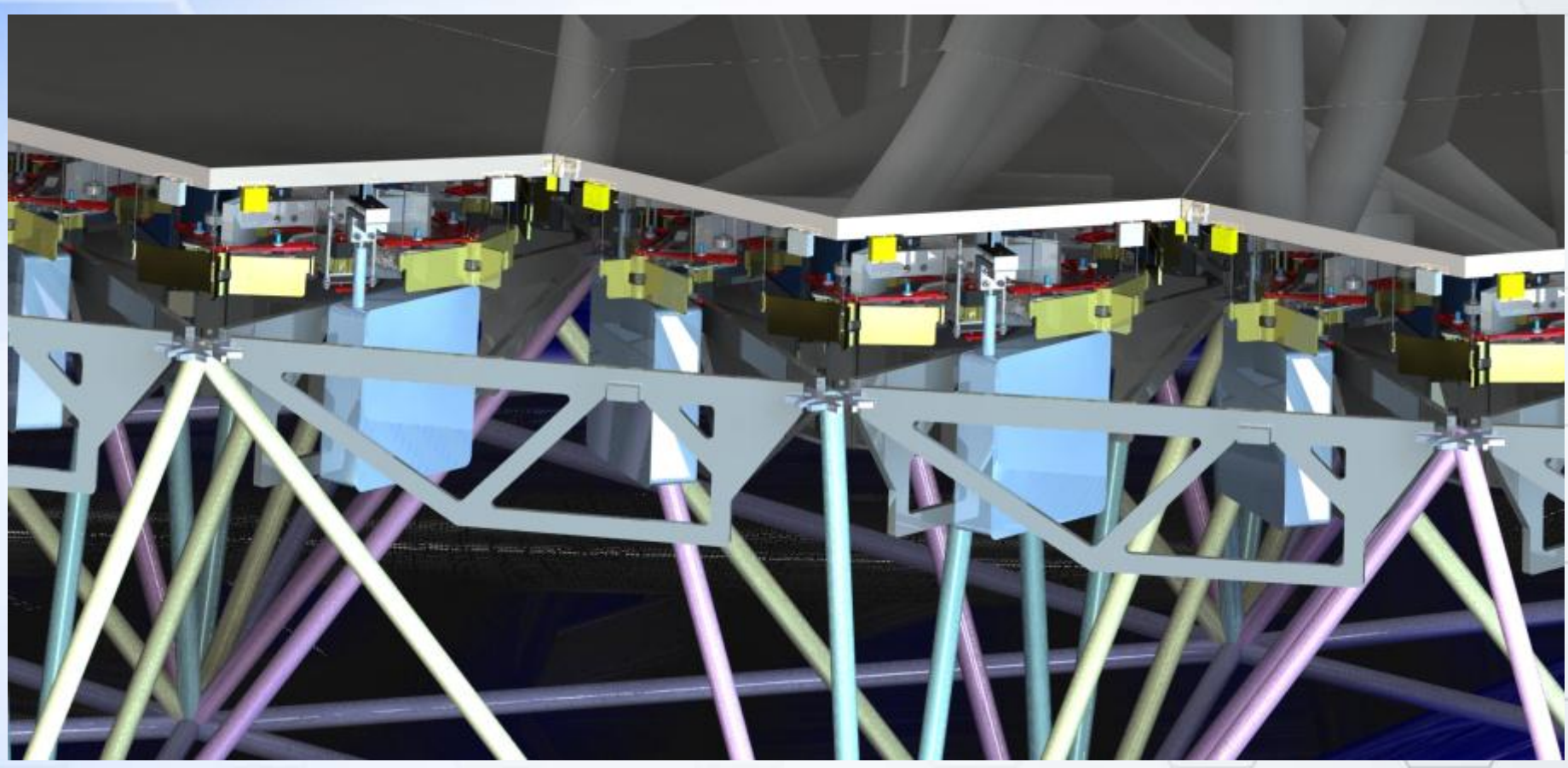
- M1CS does not directly utilize optical sensors
- The alignment and phasing system (APS) provides the nominal zero points for M1CS control
  - APS is run every 2–4 weeks, typically following segment exchanges
- Additional low-order optical feedback is provided by the acquisition, guiding, and wavefront-sensor (AGWFS) of the Adaptive Optics (AO)



Primary Segment Assembly (PSA)



Mirror Cell

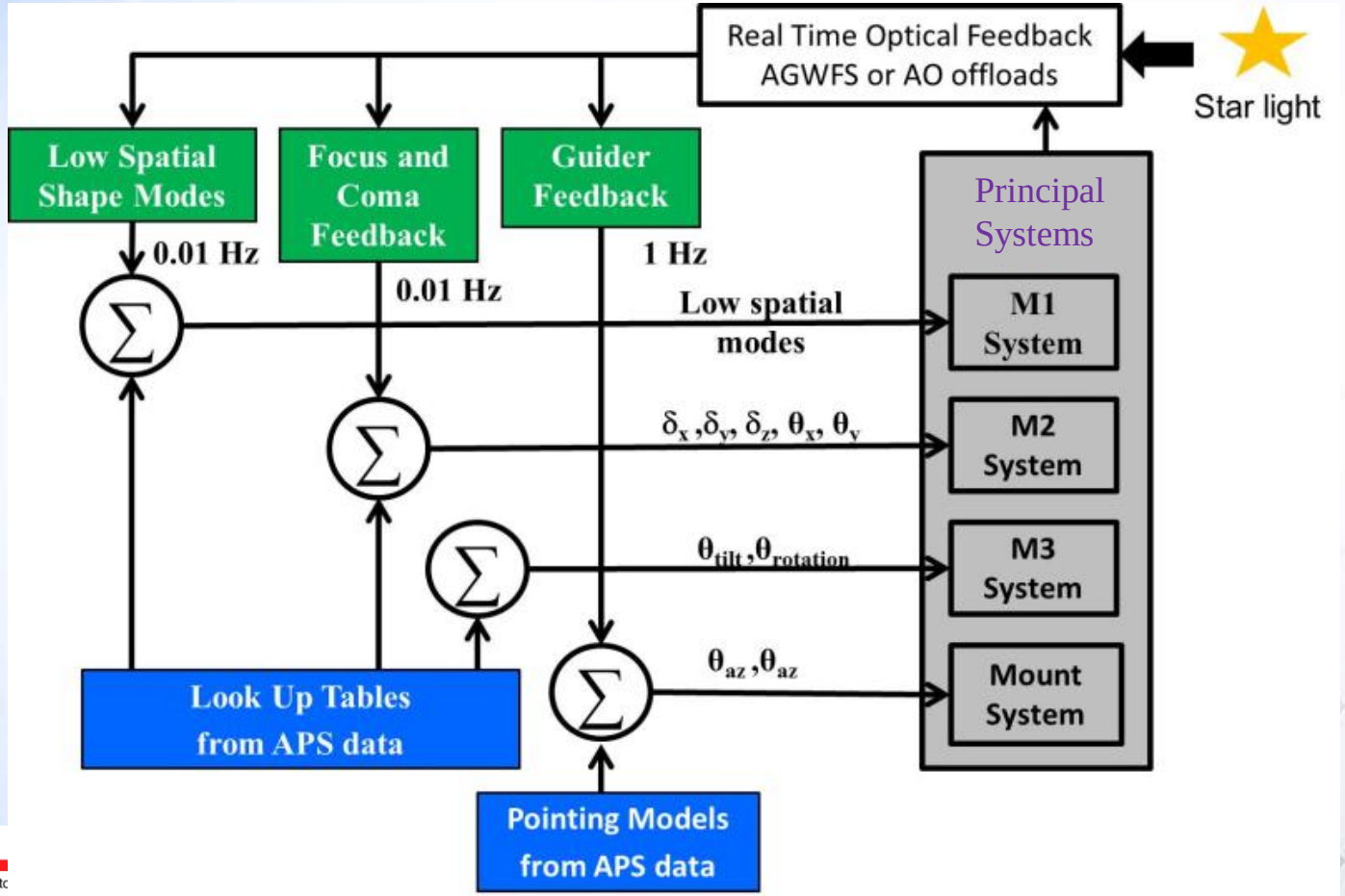


M1CS Edge Sensors

- Sense the relative positions of each of the 492 segments of TMT
- Mounted on the back of the segments
  - Two sensor halves on each inter-segment edge
  - 2772 pairs, total (each pair = one sensor)
- Incorporate integral electronics
- Measure
  - Output 1: sum of
    height difference between segments
    + (dihedral angle between segments
    × the sensor effective lever arm, Leff)
  - Output 2: gap between segments
- A sensor boot and a dry-gas purge keep the sensors clean and dry

M1CS as Part of Telescope Control

M1CS is one of several systems that maintains the shape and/or position of TMT's primary (M1), secondary (M2), and tertiary (M3) mirrors.



What is APS and What Will It Do?

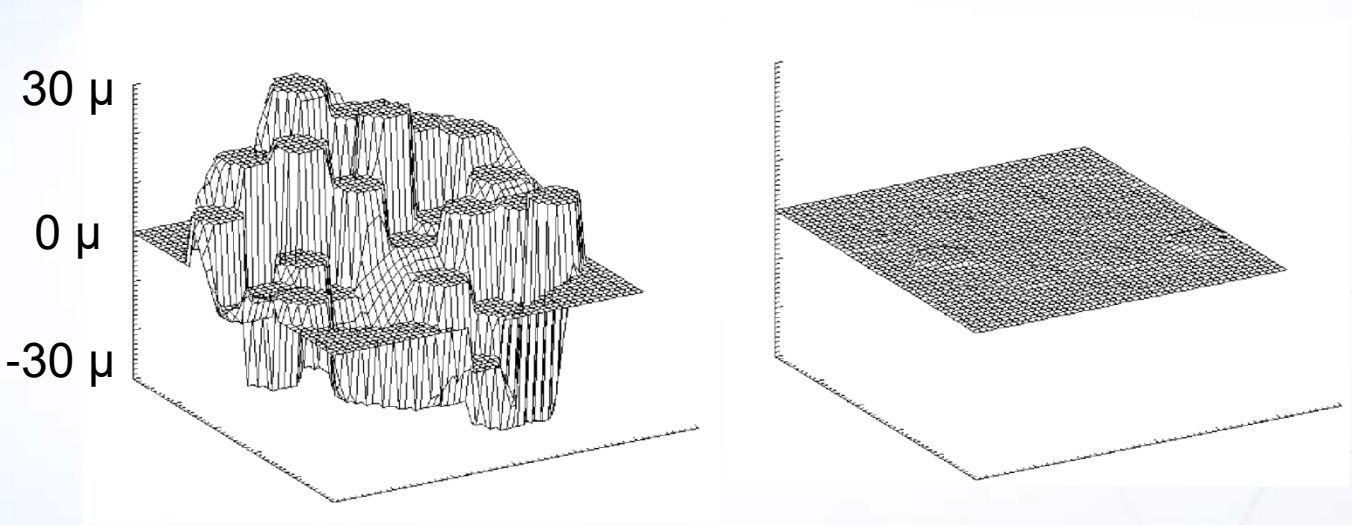
- The Alignment and Phasing System (APS) is a Shack-Hartmann wavefront sensor responsible for the overall pre-AO wavefront quality of the TMT.
- In order to produce wavefronts of acceptable quality, APS will adjust as required a total of 11,814 degrees of freedom (Dof)
  - Segment pistons, tip and tilts [492*3 DoF]
  - Segment surface figures (via warping harnesses) [492 * 21 DoF]
  - Rigid body DoFs of M2, M3 [6 total DoF]
- Align the telescope in less then
  - 120 minutes after a segment exchange
  - 30 minutes when performing a maintenance alignment

Keck PCS System Summary

- PCS is an F/15 camera that is responsible for:
  - Tip/tilt alignment of the segments
  - Phasing of the segments
  - Positioning in tip/tilt/piston of secondary (M2)
  - Measurements of segment surface errors for warping of segments
- PCS delivery dates: K1:1989; K2:1994
- Two almost identical systems installed
- Software and computers are identical for the 2 telescopes
- 60,000 lines of executable code and 500 functions
- Used by OAs ~1 night/telescope month
- Used for 39 telescope-years
- Successfully phased both telescopes > 600 times (combined)

Alignment and Phasing

- Techniques were developed on Keck 1
- Worked the first night on Keck 2



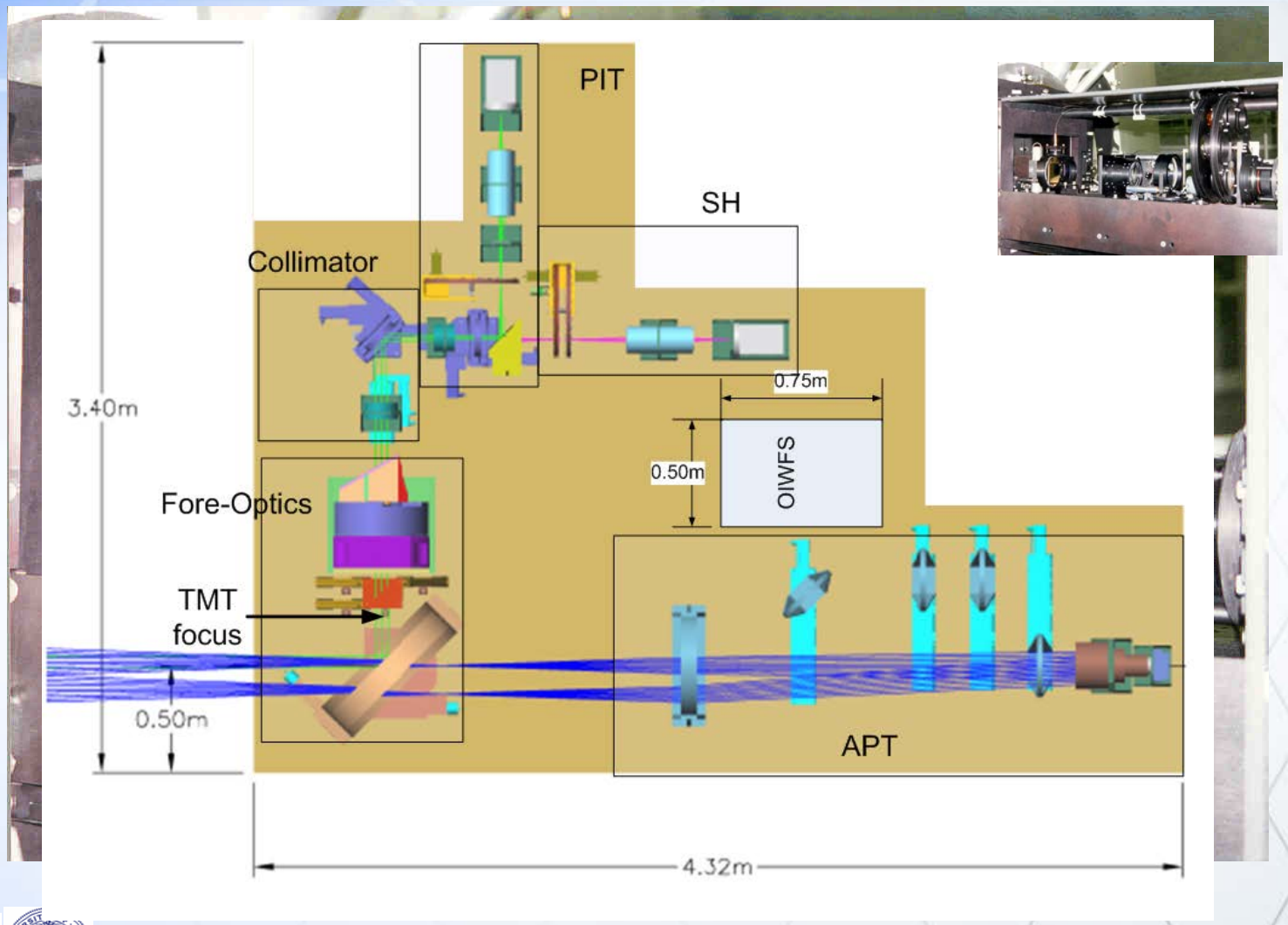
Before After

First Light on Keck 2 PCS

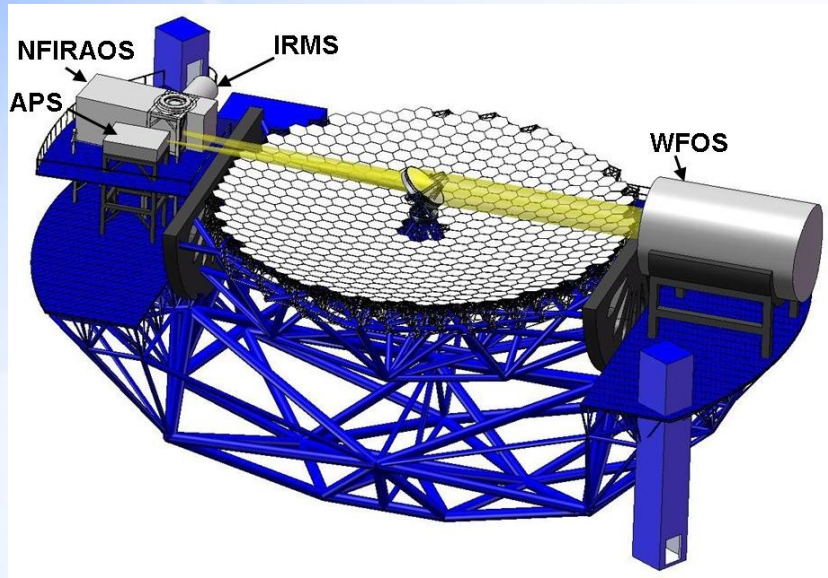
Keck/PCS vs. TMT/APS

	Keck/PCS	TMT/APS
Optical bench size	~0.6 by 1.2 m	~3 by 4 m
Telescope pupil	Does not rotate	Rotates
Phasing mask	Uses micro-prisms	Fresnel propagation: clear apertures
Number of subimages	~500	~30,000
Degree of automation	Some	Very high
Incomplete mirror operation	Not required/not often used	Will occur often and non-island configurations must be supported
Warping harnesses	Standalone algorithms, manual adjustment	Algorithms incorporated into APS, automated motors
Perform off-axis wavefront measurements	No	Yes
Pupil and image tracking capability	No	Yes
Guiding capability	No	Yes

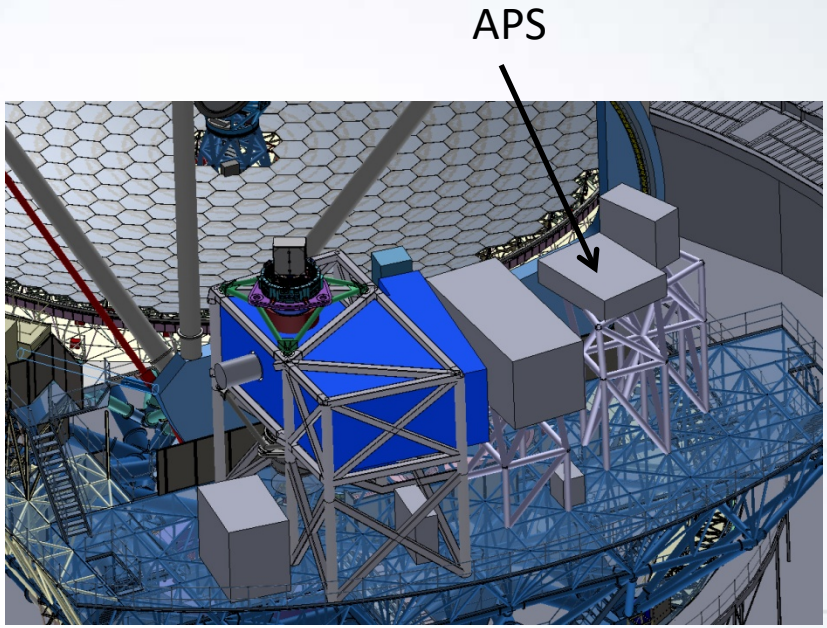
APS & PCS Optical Benchs



APS Location



APS mounted on the elevation axis

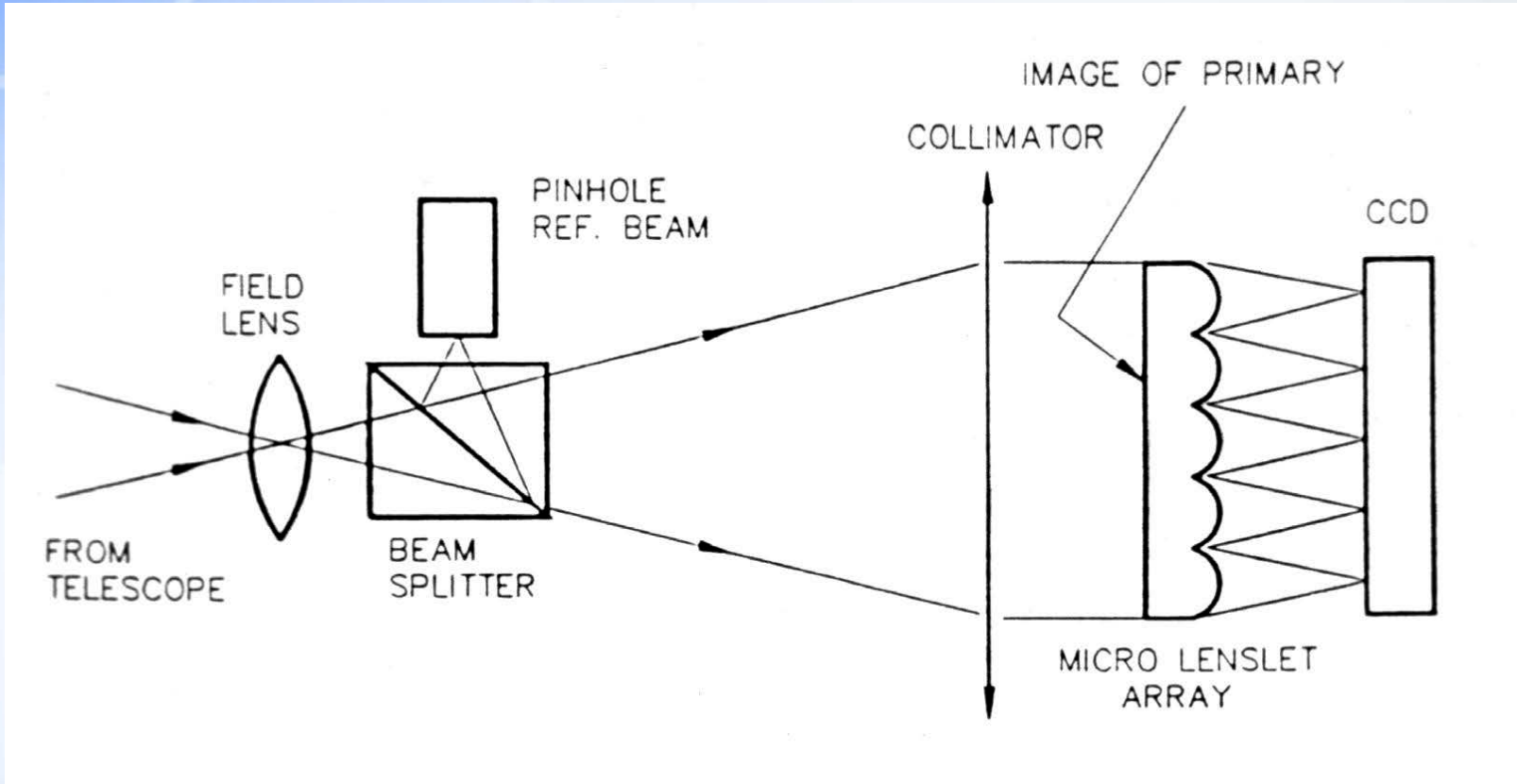


APS mounted off the elevation axis

Outline of Phasing Topics

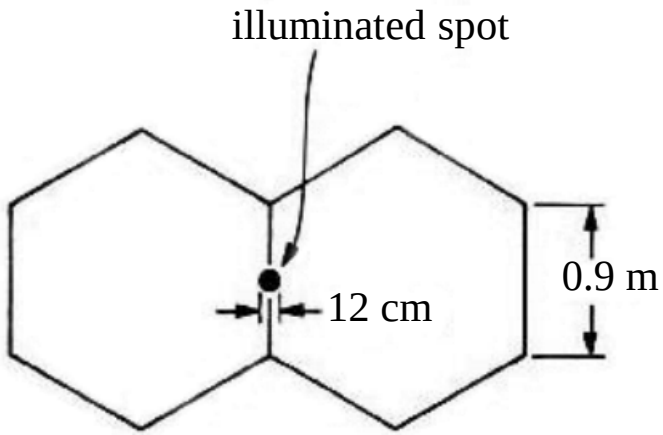
- Review of current telescopes and techniques
- Basic description of "Shack-Hartmann" phasing
- Narrow band phasing – capture range +/- $\lambda/4$
  - How it works
  - On-sky Keck results
  - Testbed results
- Coherence phasing – capture range >> +/- $\lambda/4$
  - How it works
  - On-sky Keck results
- Phasing is the adjustment of segments in piston degree of freedom only

Shack Hartmann Test

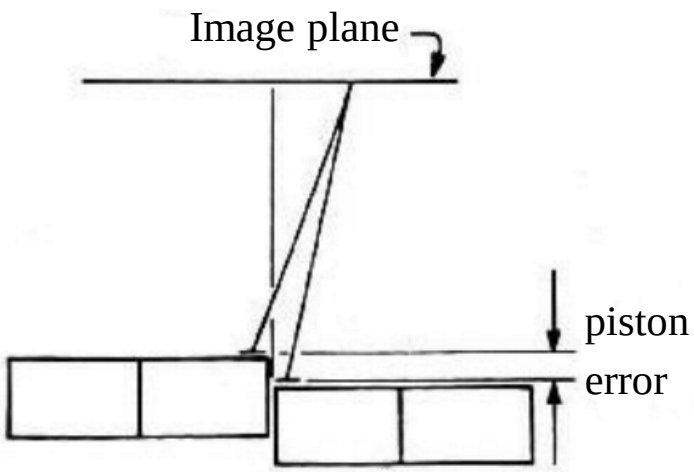


Segment Phasing

Top View



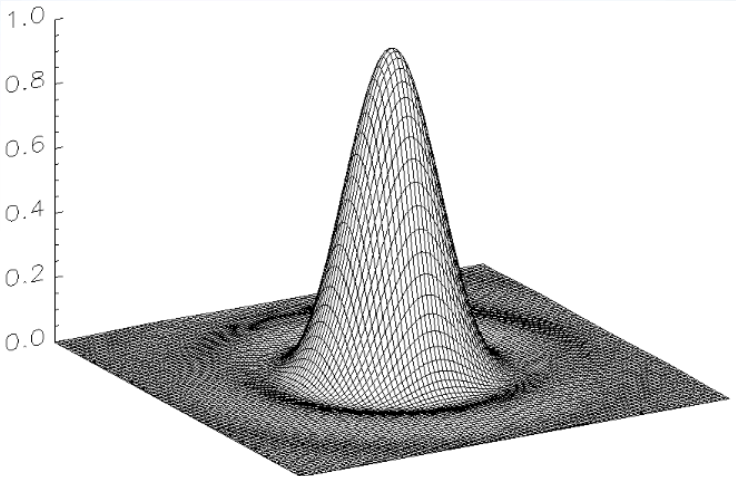
Side View



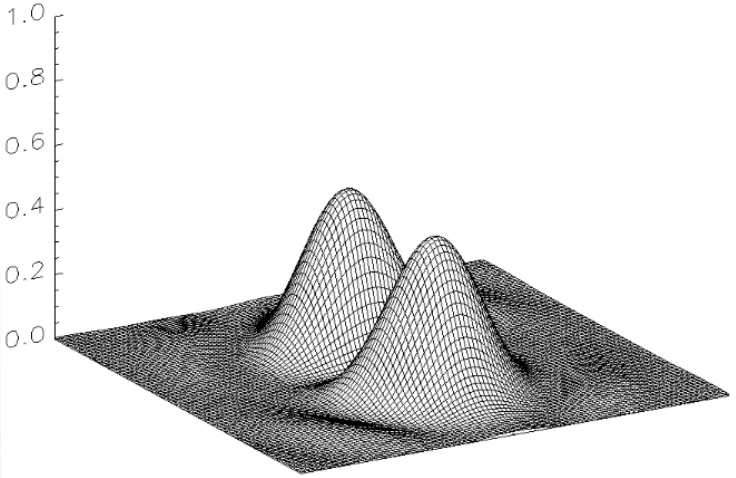
- Phasing subaperture size selected to be smaller then r_0.

In and Out of Phase Subimages

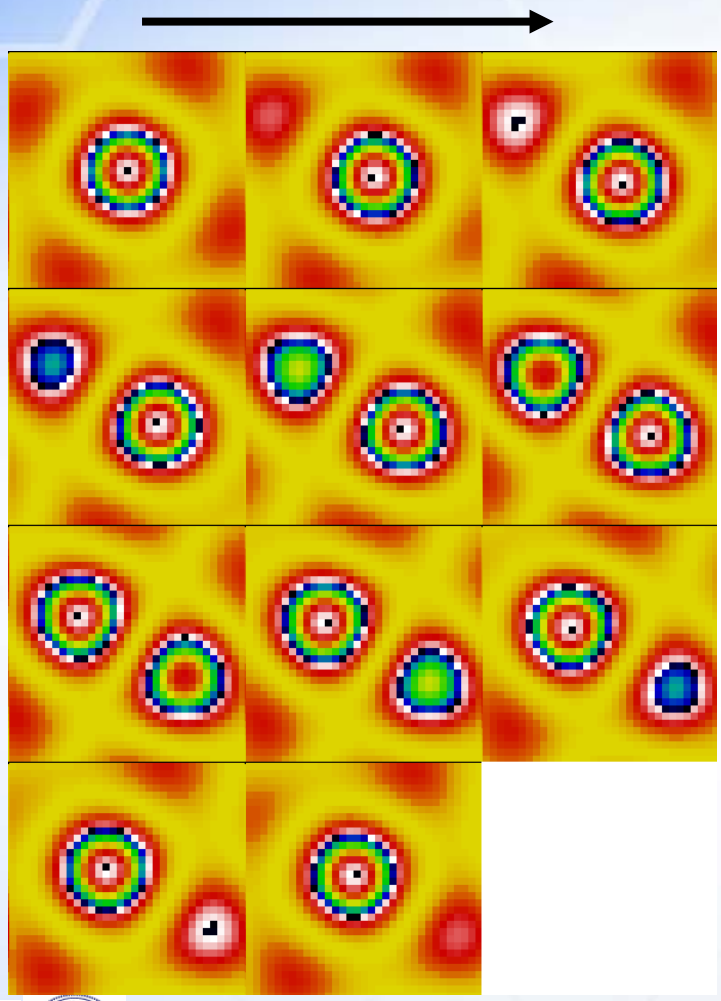
$$\text{Piston Error} = 0$$

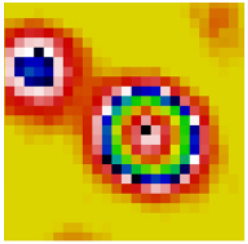


$$\text{Piston Error} = \frac{\lambda}{4}$$



Phasing Template Sequence
(891 nm filter, 10 nm FWHM)

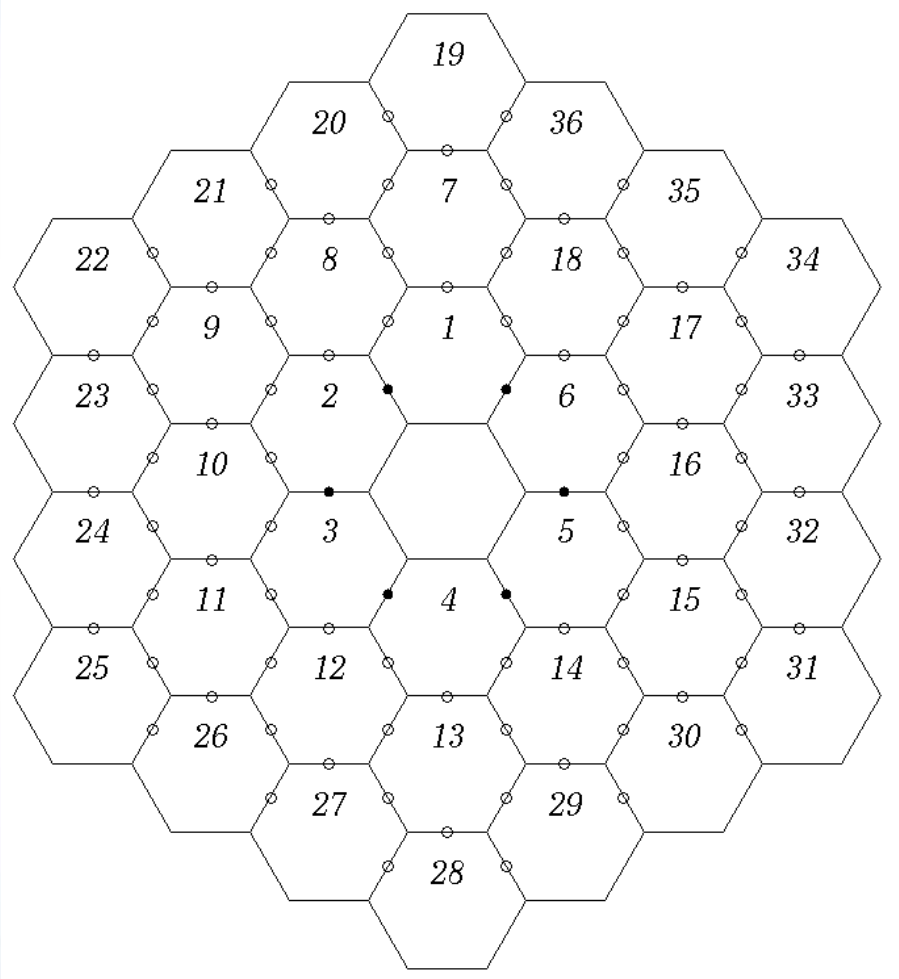




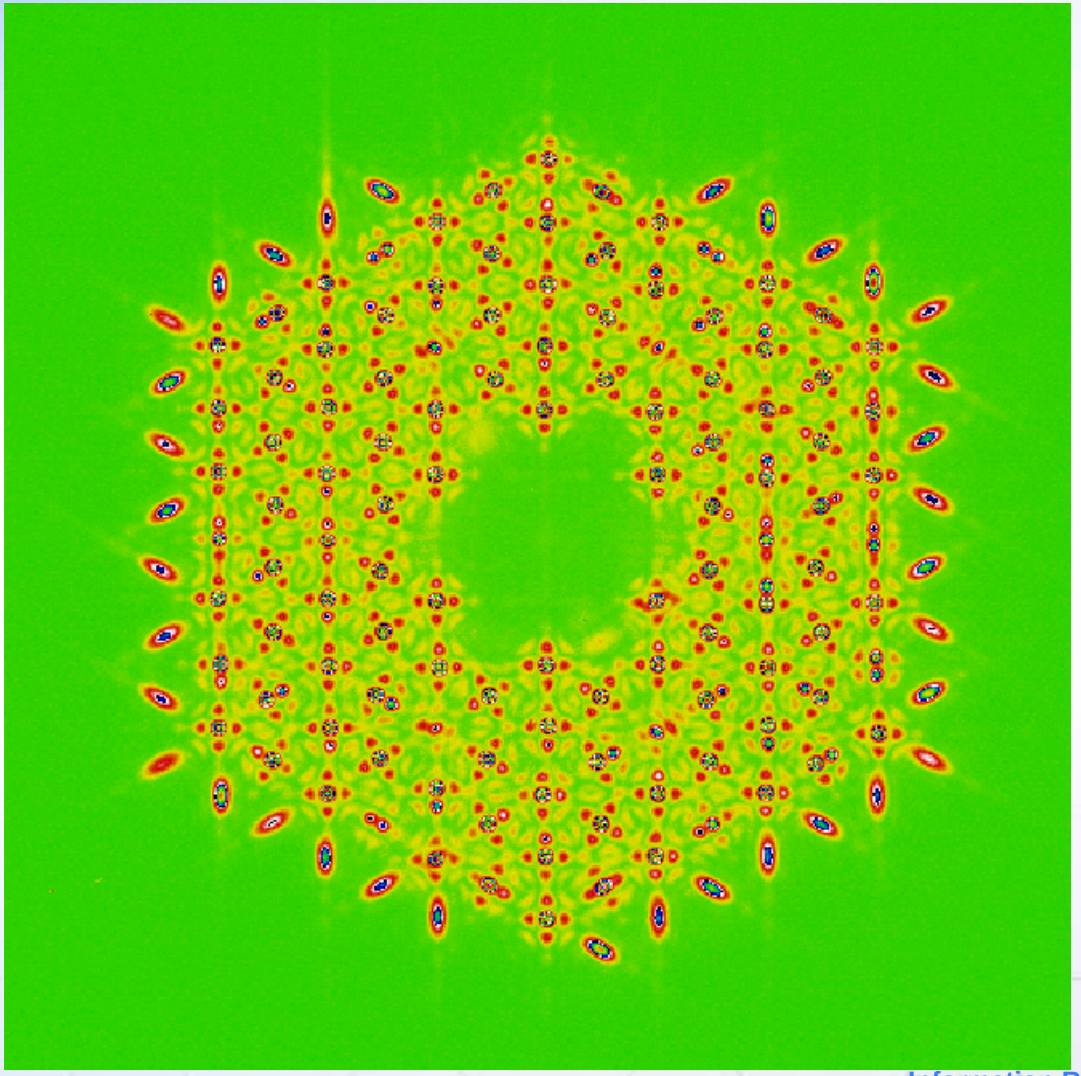
$$\text{Step Size} = \frac{\lambda}{22} = 40 \text{ nm}$$

Phasing Keck Telescope

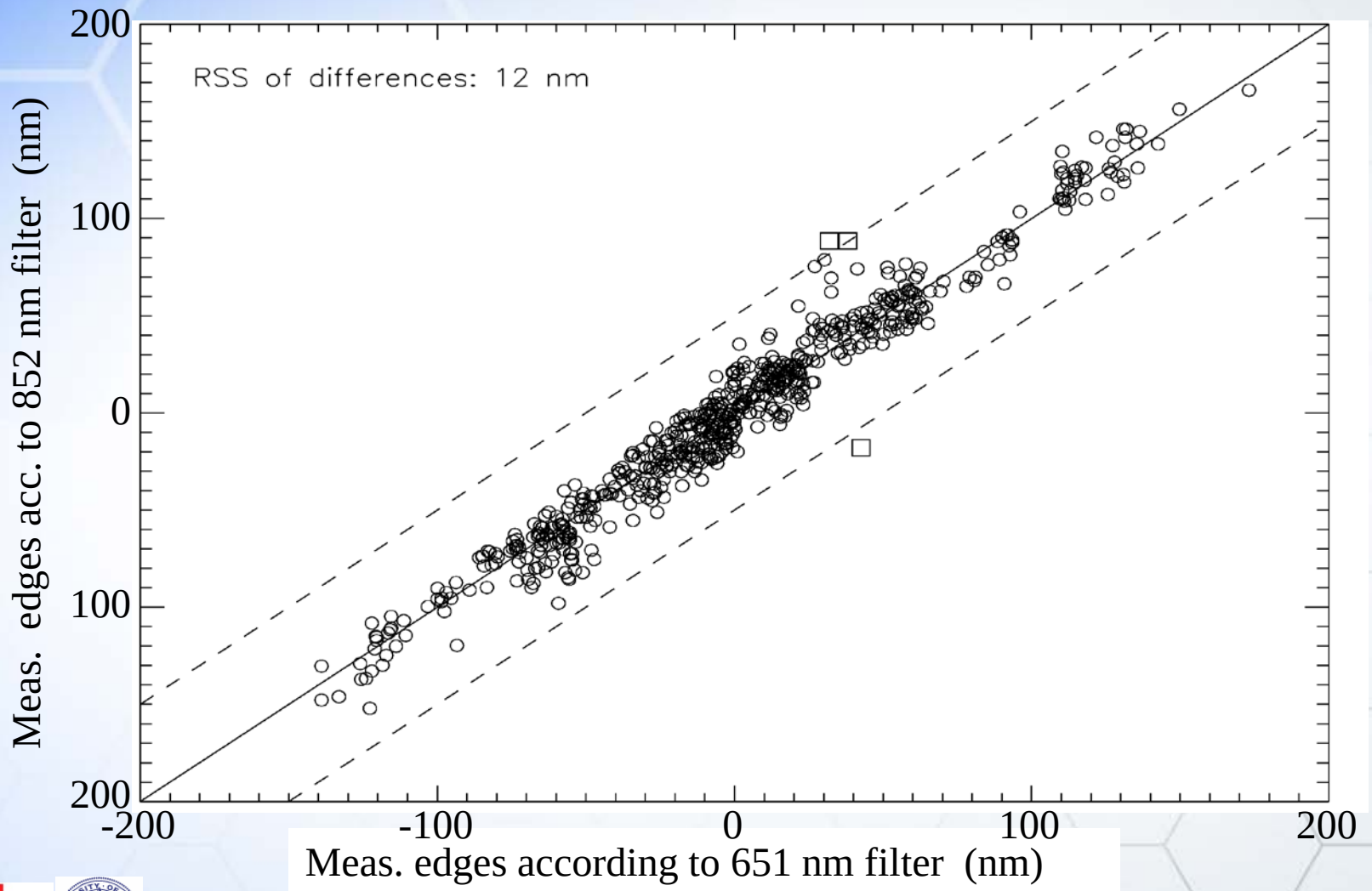
- 78 edge-sampled spots used in phasing
- 120 mm diameter



Narrowband Phasing – Keck Data (852 nm filter)

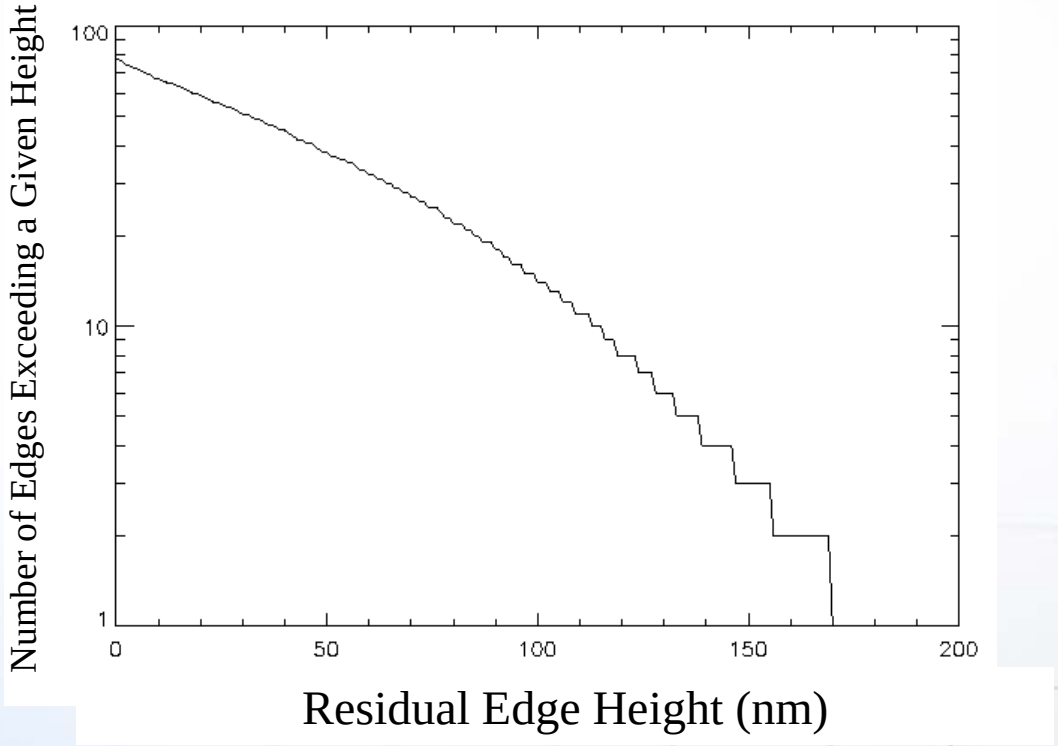


Phasing: 852 nm vs 651 nm

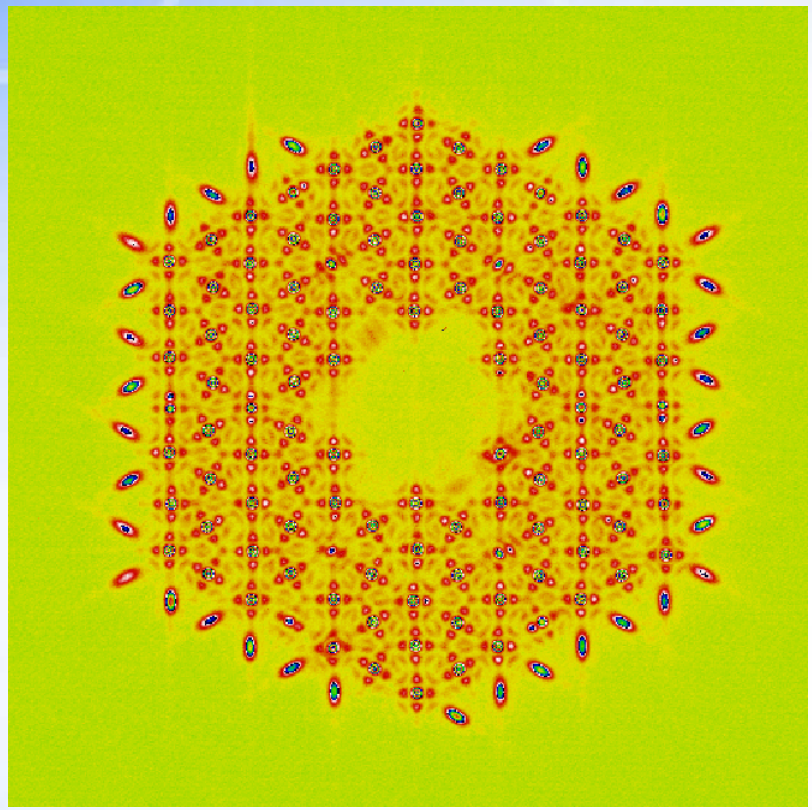


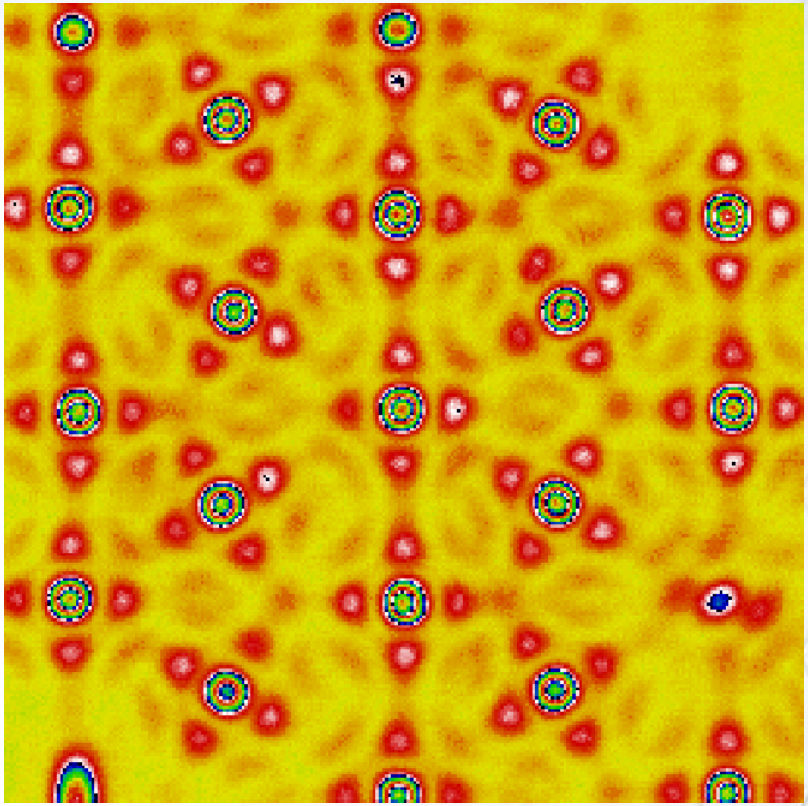
Narrowband Phasing Limitation

- When edge step approaches λ/4 (220 nm), measurement becomes uncertain by λ/2
- "Effective" capture range reduced to: 220 nm – max edge residual



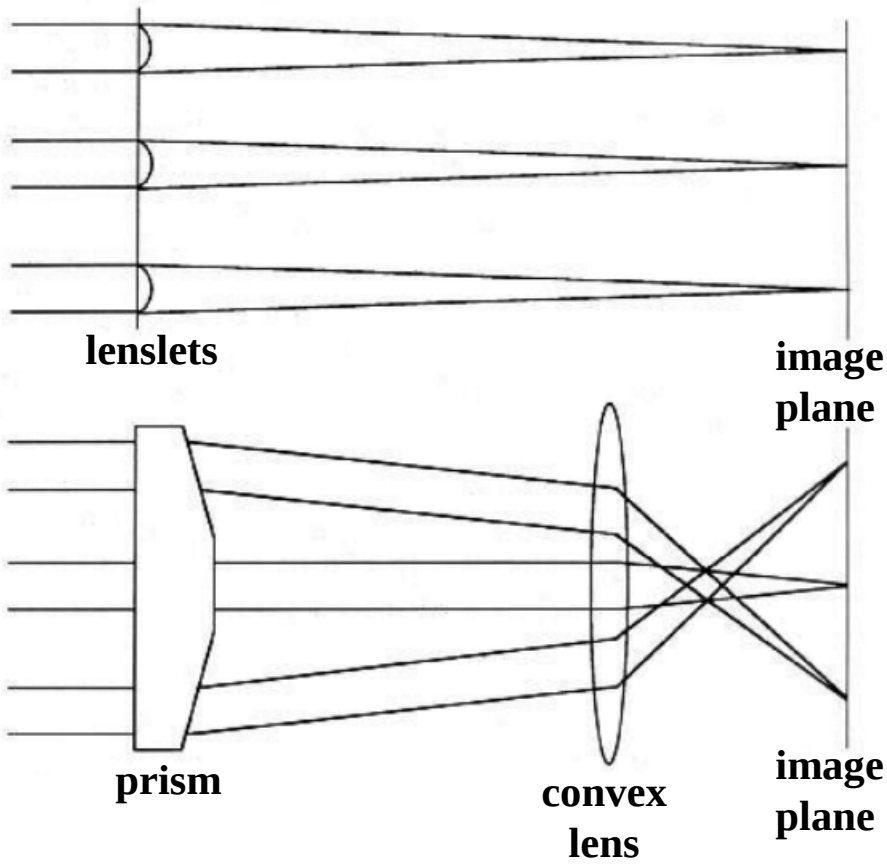
Phasing with Perfect Segments (use Segment Tip/Tilt to align edges)





- Piston RMS = 2 nm
- RMS edge residual = 9 nm

Multiple Choices for Forming Sub-Images Lenslets, Prisms, Masks

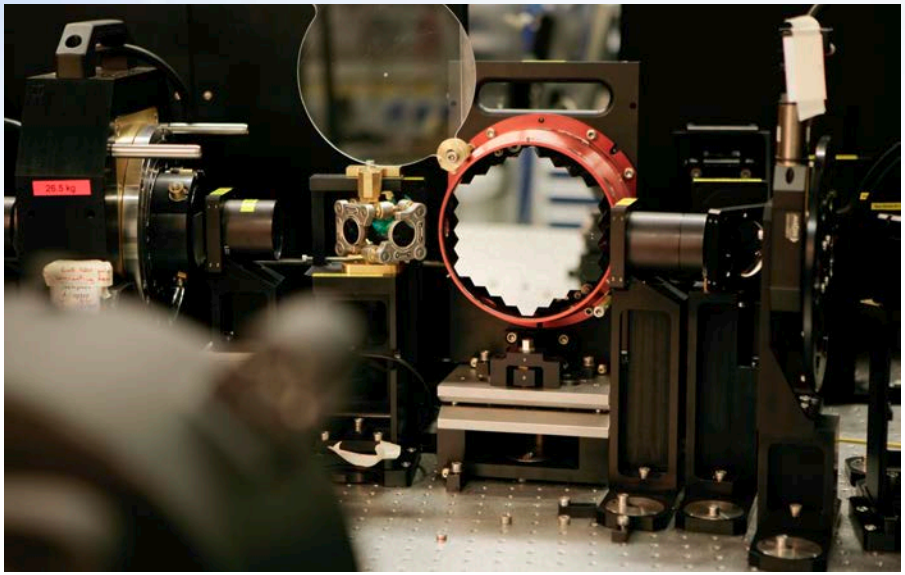


- Lenslets
  - Need to worry about quality
  - Commercially available
  - Expensive
- Prisms
  - Good image quality
  - Hard to make large arrays
- Masks (Fresnel diffraction)
  - Good image quality
  - Inexpensive
  - System parameters define if this approach will work

Fresnel Phasing

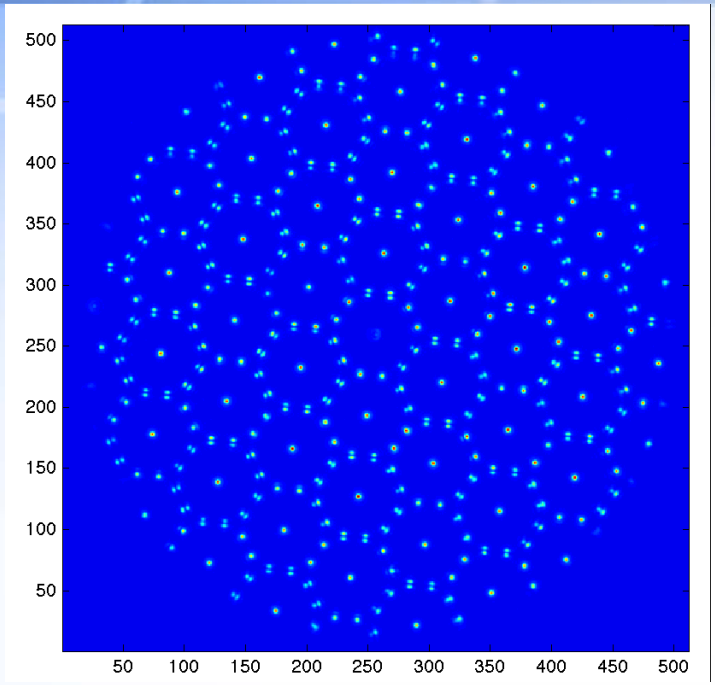
- Fresnel number of a lens: $F = a^2/f\lambda$
  - a = radius of lens
  - f = focal length of lens
  - λ = wavelength of observation
- For $F < 1$, Fresnel and Fraunhofer diffraction patterns are very similar.
- This means that to a first approximation one can replace the lenslet array with a mask consisting of clear apertures.
- For the nominal design of the TMT Alignment and Phasing System, the Fresnel number of the lenslets is $F = 0.6$. [The Keck system has $F = 1.3$.]

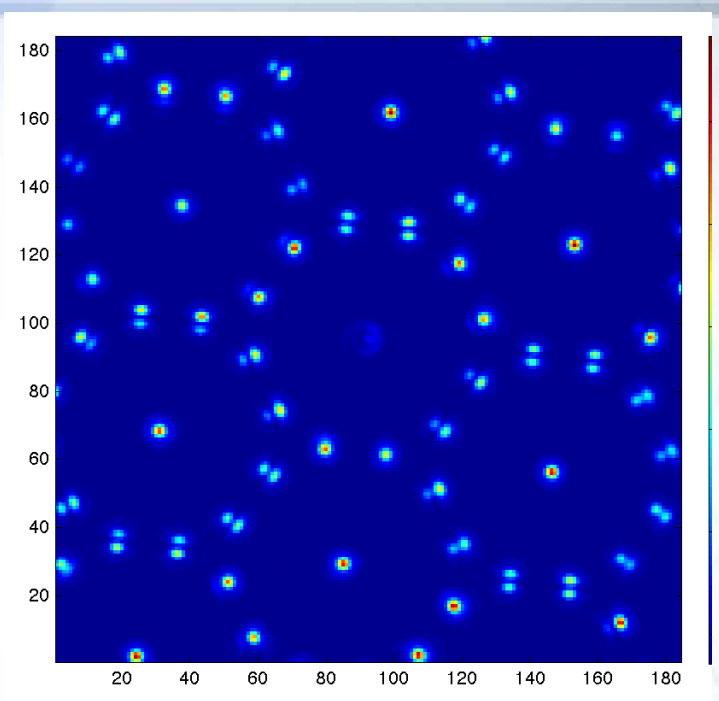
ESO Alignment and Phase Experiment



- The ESO Active Phasing Experiment (APE), originally conducted at the VLT, has been set up in the ESO optical labs.
- APE, with its 61 segment actively controlled mirror, provides an ideal testbed for Fresnel phasing.
- We conducted a series of experiments at ESO using APE to confirm Fresnel phasing (with generous support from ESO).

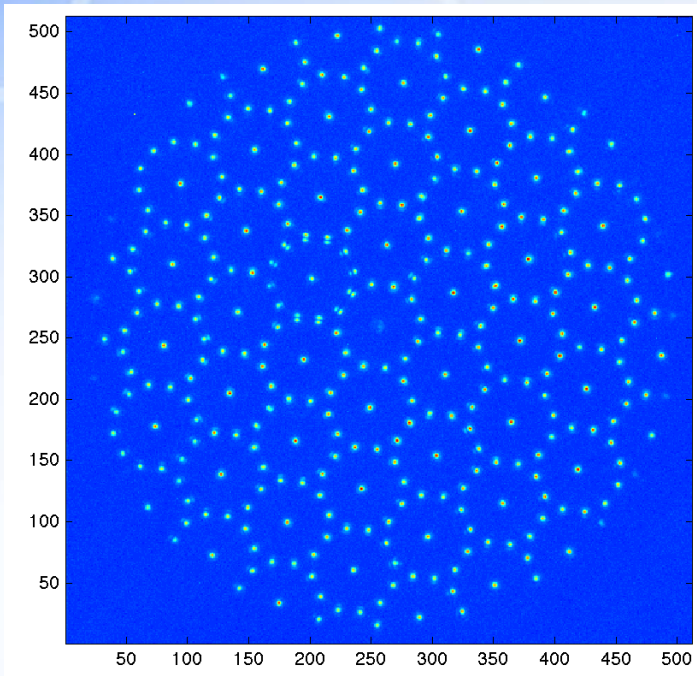
Sample Phasing Image I

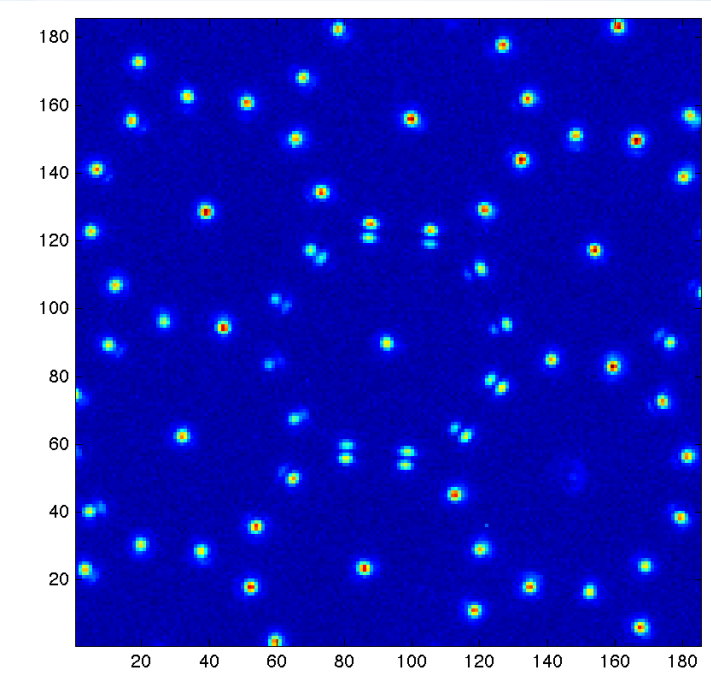




- APE phasing image: all edge steps have 0 (circular subimages) or $\lambda/4$ (split subimages) phase errors.

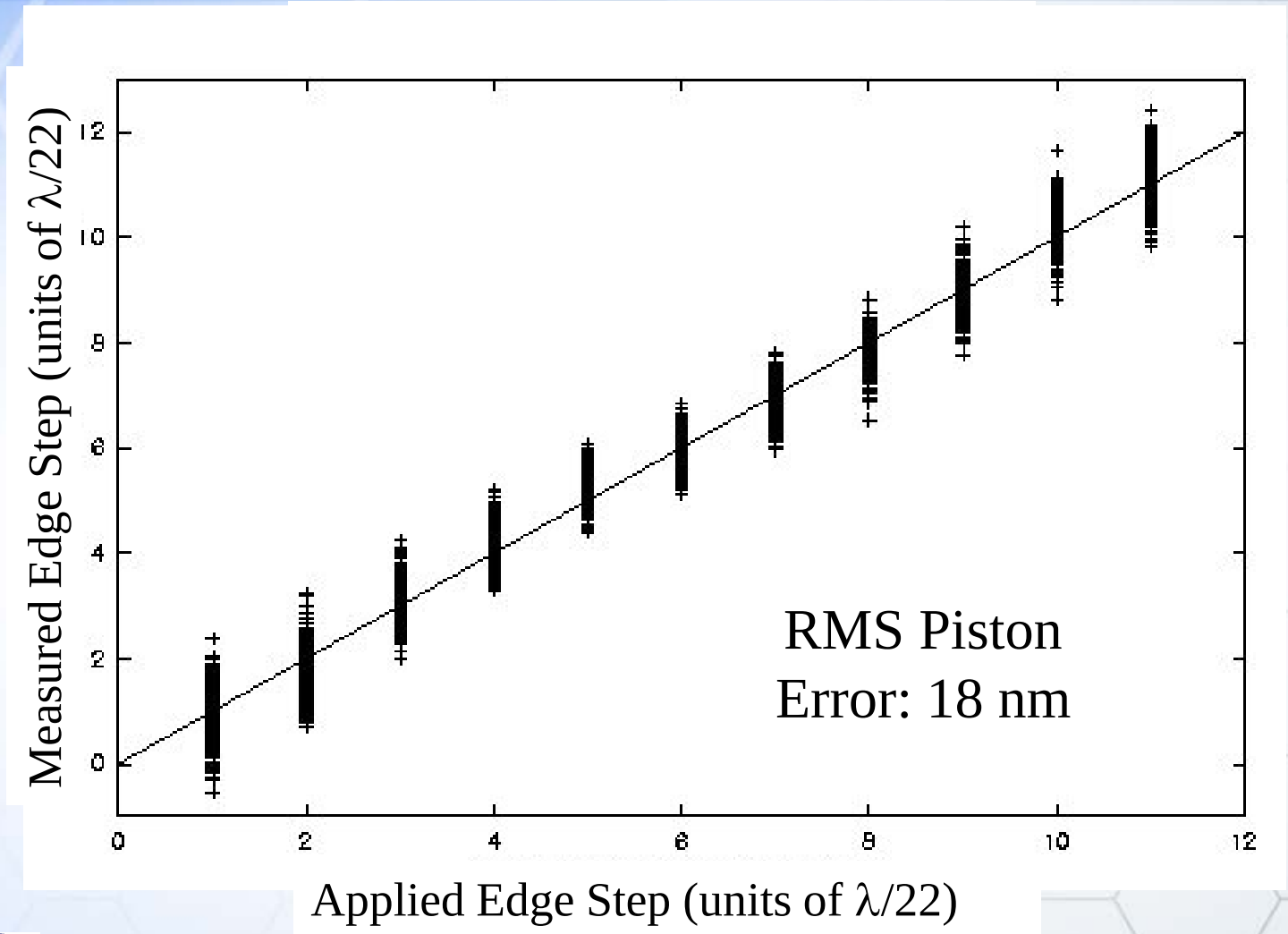
Sample Phasing Image II



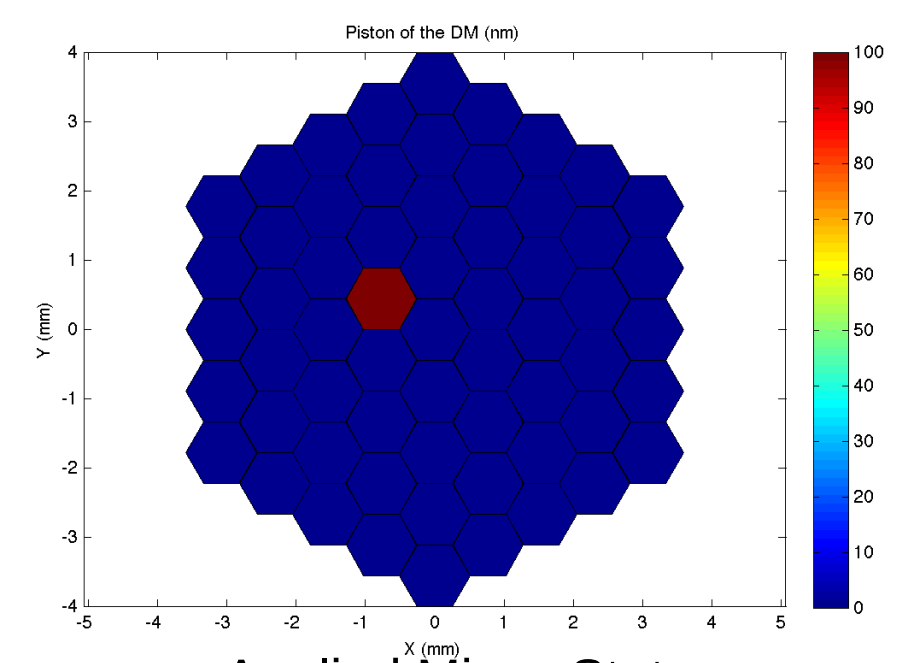


- APE phasing image: one segment pistoned by 100 nm.

Measured vs. Theoretical Edge Steps – Fresnel Phasing

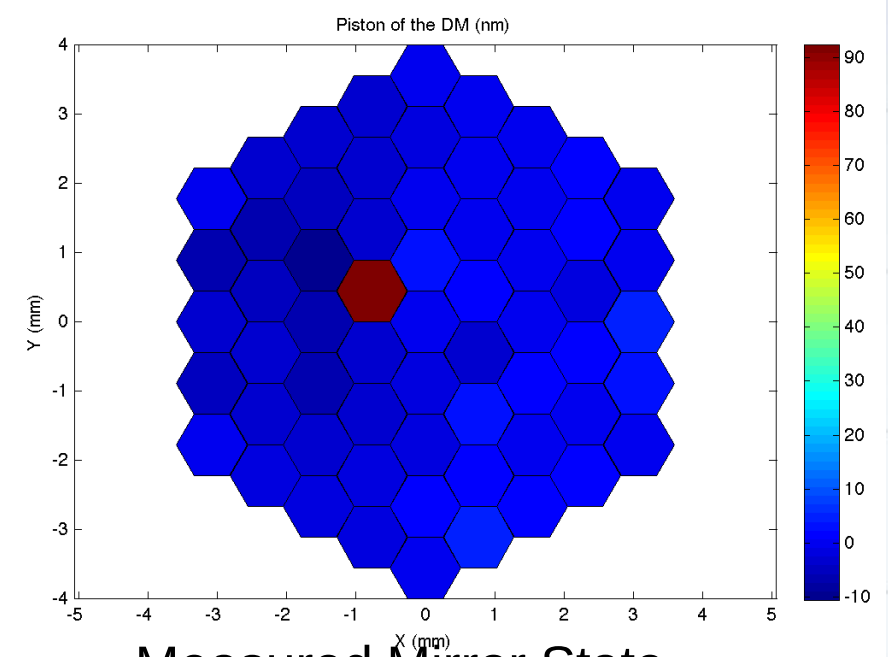


Measuring Piston Error of a Single Segment



Applied Mirror State

(Segment Piston = 100 nm)

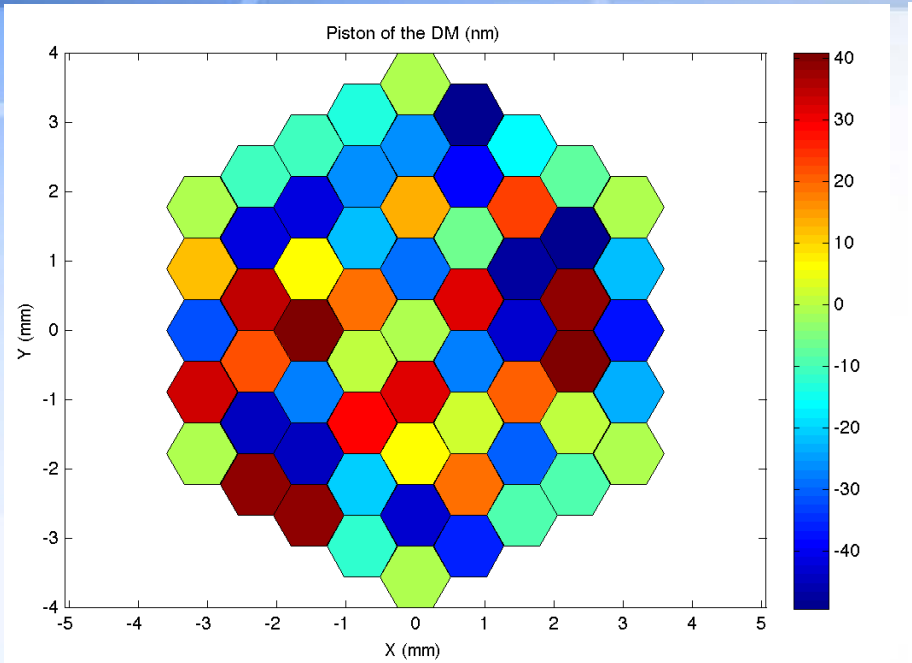


Measured Mirror State

(Segment Piston = 93 nm)

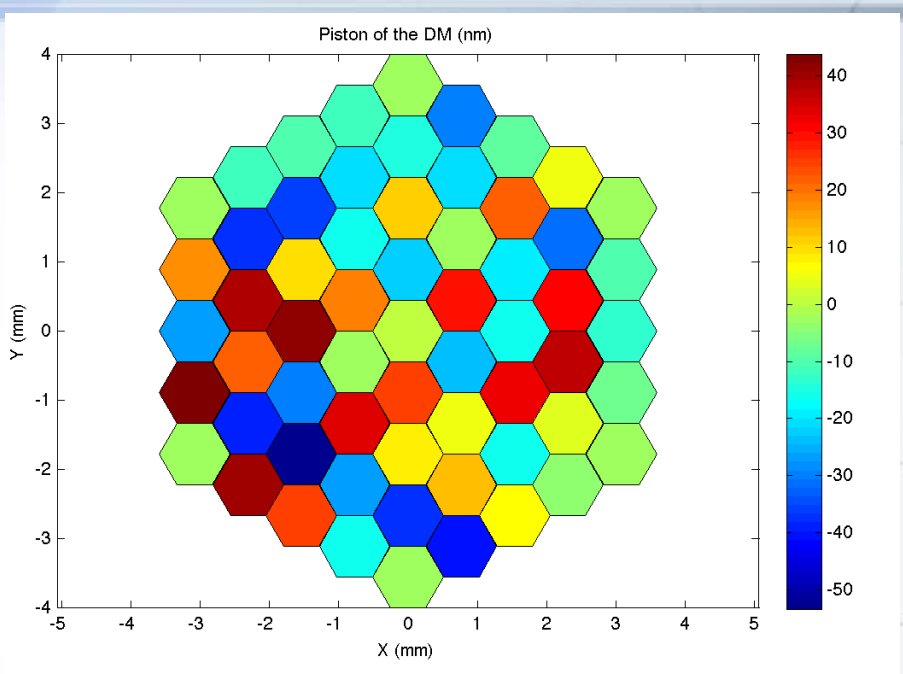
- Error in segment piston from first measurement = 7.0 nm
- Error in segment piston after 2 iterations = 2.0 nm

Measuring A Random Mirror Configuration



Applied Mirror State

(RMS = 29 nm)



Measured Mirror State

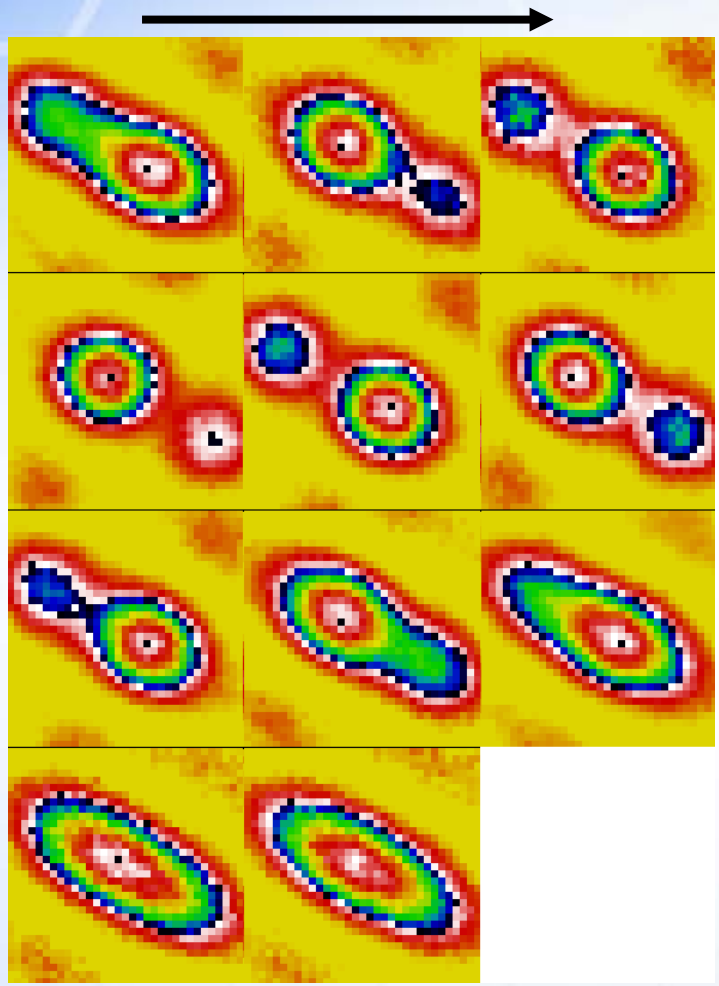
(RMS = 24 nm)

- RMS piston error of first measurement = 9.0 nm
- RMS piston error after sending 2 iterations times = 3.6 nm

Coherence Phasing

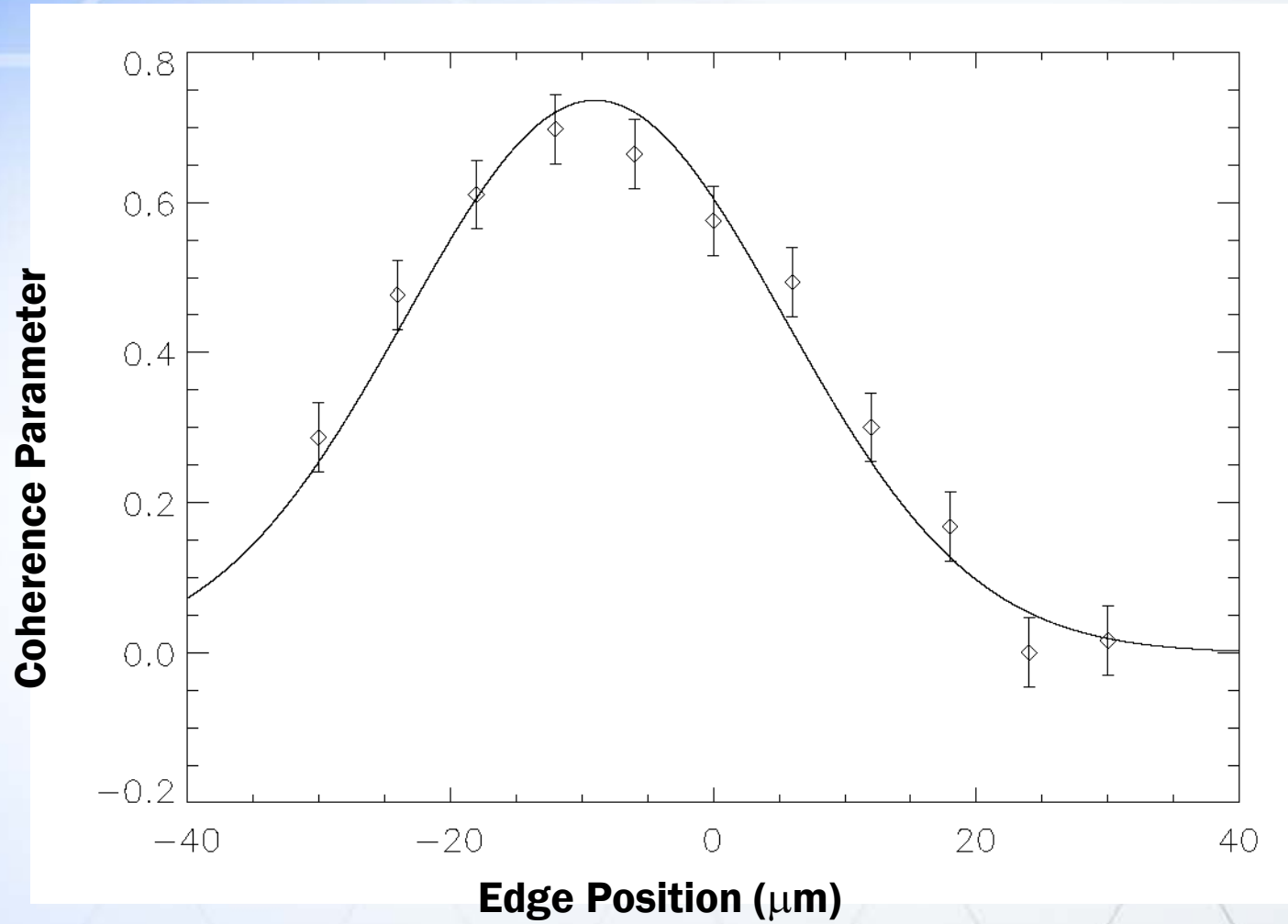
- Exploits the broadband nature of light
- When the phase step exceeds the coherence wavelength the image becomes a superposition of multiple in-phase subimages resulting in an elongated sub-image $\frac{\lambda^2}{2\Delta\lambda}$
- We quantify this with the coherence parameter:
  - Maximum correlation – Minimum Correlation
- Each segment edge is stepped through 11 different phase steps and the coherence parameter calculated.
- The resulting coherence parameters are fit to a Gaussian and the edge step error calculated

Typical Broadband Sequence (Actual Keck Data)



- Step Size = 6 μm
- Coherence Length = 40 μm
- (891/10 filter)

Coherence vs. Edge Step – Keck Data (891/10 nm)



Broadband Phasing Parameters

Mode	Wave-length nm	Bandwidth nm	Coherence Length μm	Step Size μm	Accuracy nm	Capture Range μm	Star Magnitude V
Phasing-1000	891	10	40	6	1000	±30	4
Phasing-300	852	30	12	2	300	±10	5
Phasing-100	870	100	3.8	0.6	100	±3	6
Phasing-30	700 [eff]	200 [eff]	1.2	0.2	30	±1	7

- Capture range and accuracy for a specific application can be optimized by changing the number of steps and the coherence length of the filters used.

Solving 2π Ambiguities: Coherence Length Is a Better Approach

- Synthetic Wavelength
  - Defined by $\frac{\lambda_1 \lambda_2}{\lambda_1 - \lambda_2}$
  - 30 µm to ¼ λ in 4-6 exposures
  - Highly sensitive to meas. Uncertainty and Systematic Errors
  - Gives wrong answer if out of range (see Lofdahl & Erikson)
  - Don't need to move segment
- Coherence Length
  - Defined by $\frac{\lambda^2}{2\Delta\lambda}$
  - 30 µm to ¼ λ in 22 exposures
  - Moderately sensitive to meas. Uncertainty
  - Gives no answer if edge step out of range
  - Must move segments

- Initial segment alignment errors and segment aberrations mean that edges are often out of range
- APE Experiments confirmed problems with artificial wavelengths
- Getting one edge wrong will "propagate" through the whole mirror
- The coherence technique essentially guarantees you don't get the wrong answer

Ground-Based Optical Segmented Telescopes-Phasing Techniques

- Keck : “Shack-Hartmann” Phasing (used >1000 times)
- GTC: “Shack-Hartmann” Phasing
- ESO Alignment and Phasing Experiment
  - SHAPS: “Shack-Hartmann” Phasing
  - ZEUS: “Zernike Unit for Segment Phasing”
  - PYPS: “Pyramid Phase Sensor”
  - DIPSI: “Diffraction Image Phase Sensing Instrument”
- Planned telescopes
  - Thirty Meter Telescope (TMT): “Shack-Hartmann” Phasing
  - European-ELT: “Shack-Hartmann” Phasing

Phasing Methods Demonstrated at Keck

- Multiple phasing tests have been demonstrated and tested at Keck:

Phasing Technique	Accuracy (RMS Surface Error)
Broadband Shack-Hartmann	30 nm
Narrowband Shack-Hartmann	6 nm
Phase Discontinuity Sensing	35 nm
Dispersed Fringe Sensing	65 nm

2006 Feasibility Design study for a "Planet Formation Instrument for TMT"

- Investigated the impact of telescope aberrations on contrast
  - Used a nulling coronagraph as a "baseline".
  - This allowed a decoupling of the effects of contrast impacts form the diffraction suppression system and telescope aberrations.
- Relevant conclusions from that study:
  - The telescope will not limit contrast at the 10^{-8} level
  - The relatively small segment gaps do not limit contrast, but the larger obscurations from M2 and it's supports are challenging
  - Segment-to-segment reflectivity variations are an issue
    - Will require amplitude control using a 2nd DM
  - Segment phasing and telescope alignment in general is not a driver in the performance
  - Residual segment aberrations are a key driver in the performance

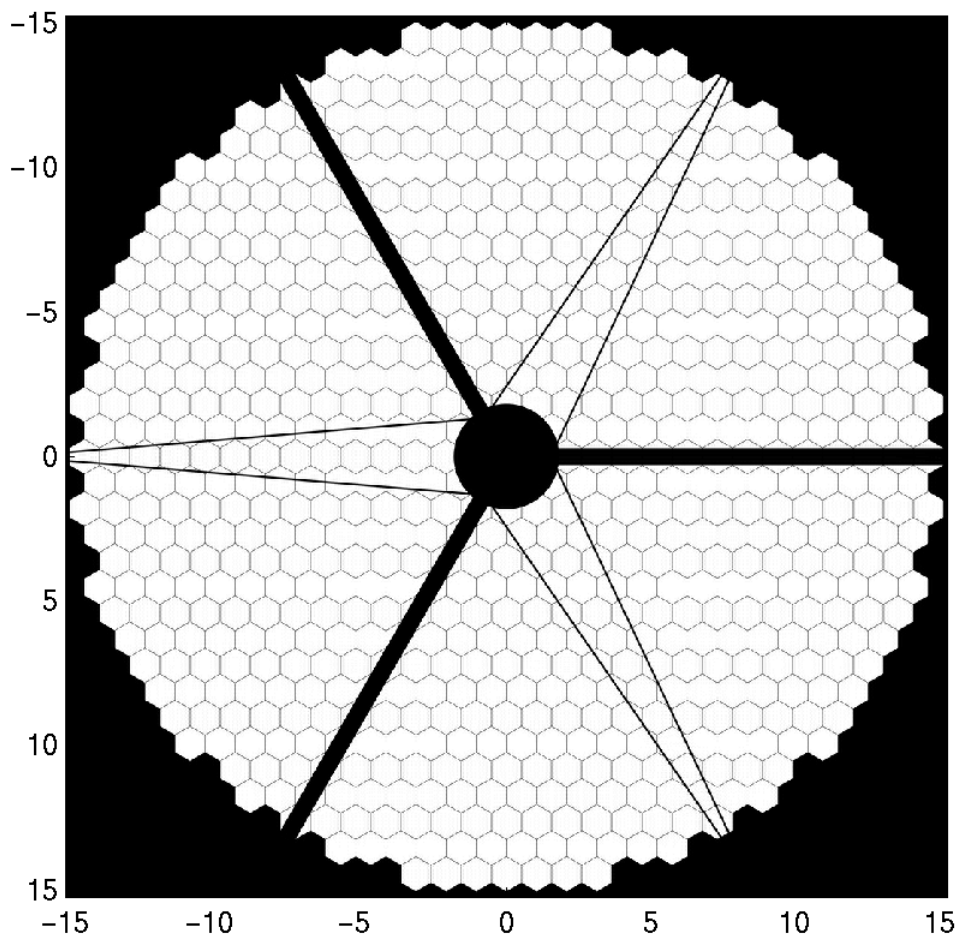
PFI Study, Continued

- Long exposure requirement after speckle suppression is 10^{-8} (goal of 10^{-9}) from 3 to ~64 λ/D (34 to ~725 milliarcsecs)
- This implies an instantaneous contrast of 2×10^{-7} (goal of 2×10^{-8})
- Investigated the following M1 static errors:
  - Segmentation and obscuration of pupil
  - Amplitude Errors
  - Segment aberrations after correction with warping harness
  - Segment alignment errors (tip/tilt and Piston)
  - Whiffletree print through

Wave-Optics Simulation

- Telescope Pupil (Fortran or Matlab)
  - 4 mm gaps would require ~32K X 32K pixel FFTs→use Gray Pixel approximation to generate pupils
    - Also generated exact central obscuration and supports
  - 1K x 1K active pupils (30mm/pixel)
  - Phase error added in pupil plane
- AO System (Uses ARROYO)
  - Wavelength:1.65 um, mono-chromatic
  - Spatially filtered Shack-Hartmann WFS with 32x32 pixels per subaperture
  - 127 x 127 Actuator DM with a least-squares reconstructor
  - Iterate until converged
- Diffraction Suppression (Matlab)
  - Lyot Coronagraph: Radial $Sinc^2$
  - Two stage Nuller with 3.12 meter shears

Segmentation and Obscuration of Pupil

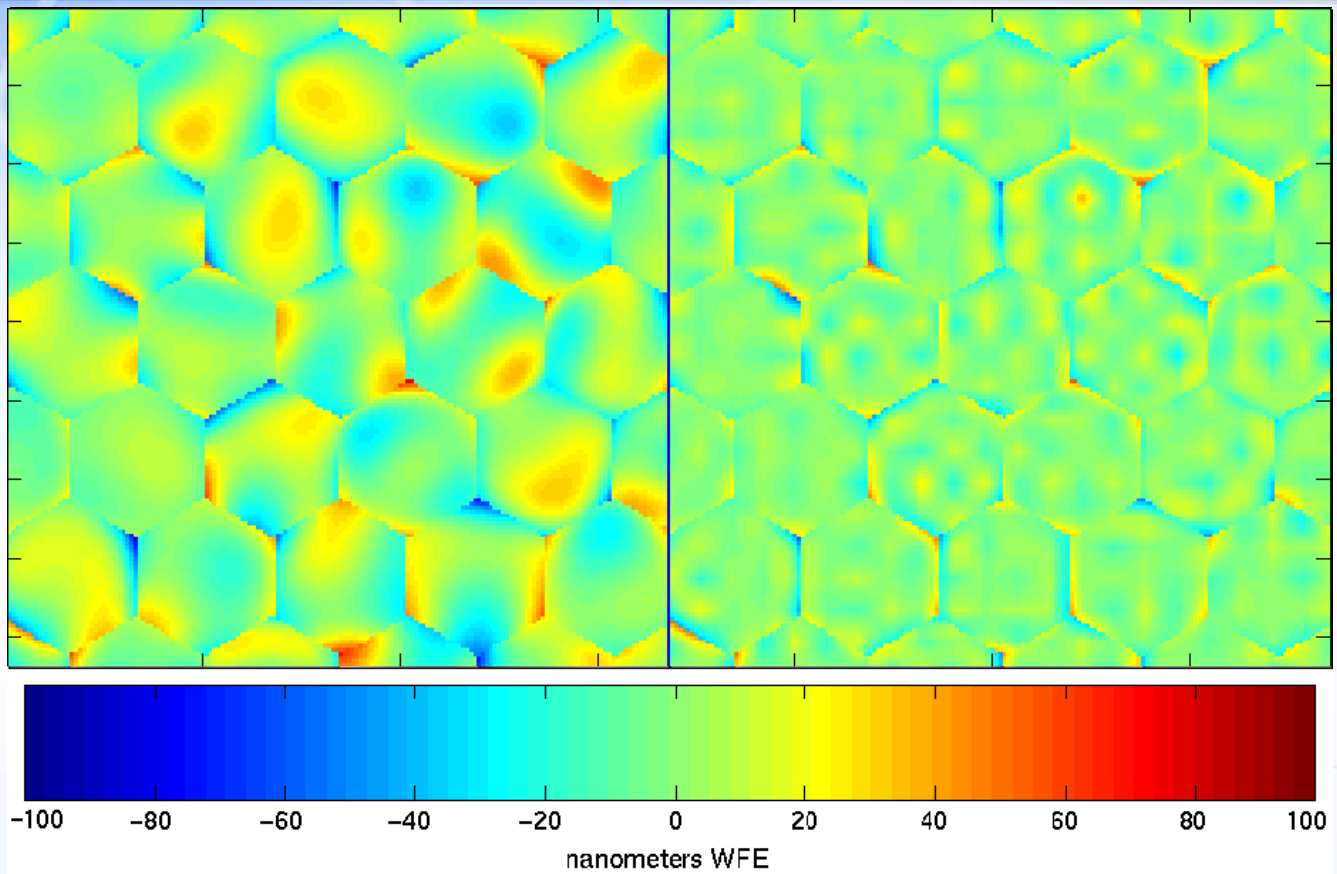


- 738 Segments
- Segments are 0.6 m on a side
- 4 mm gaps
- Central obscuration: 3.65 m circle
- 3-50 cm compression supports
- 6-10 mm support cables

Wavefront Error Table

	RMS (2006) (nm Wavefront)		RMS (2016) (nm Wavefront)	
	Pre-AO	Post-AO	Pre-AO	Post-AO
Segment Aberrations Ideal correction with Keck Meas. Errors	17.3	9.1	12.8	~13
Whiffletree print through	12.2	11.4	17.6	~16
Segment piston	12.7	4.5	13.6	~4
Segment tip/tilt	8.3	3.8	190	~5
Combined errors	23.2	**14.6**	192	**22**

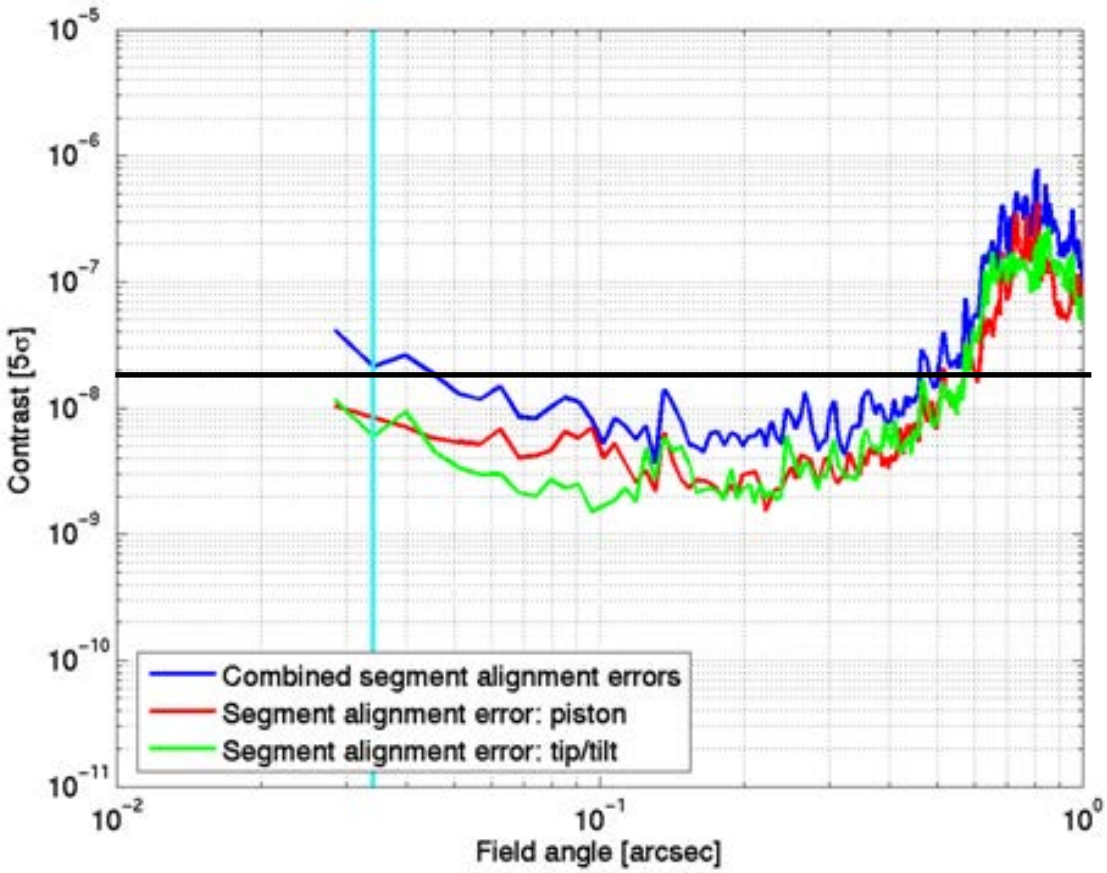
Segment Aberrations Before and After AO



- RMS: 17.3 nm
- P-V: 242 nm

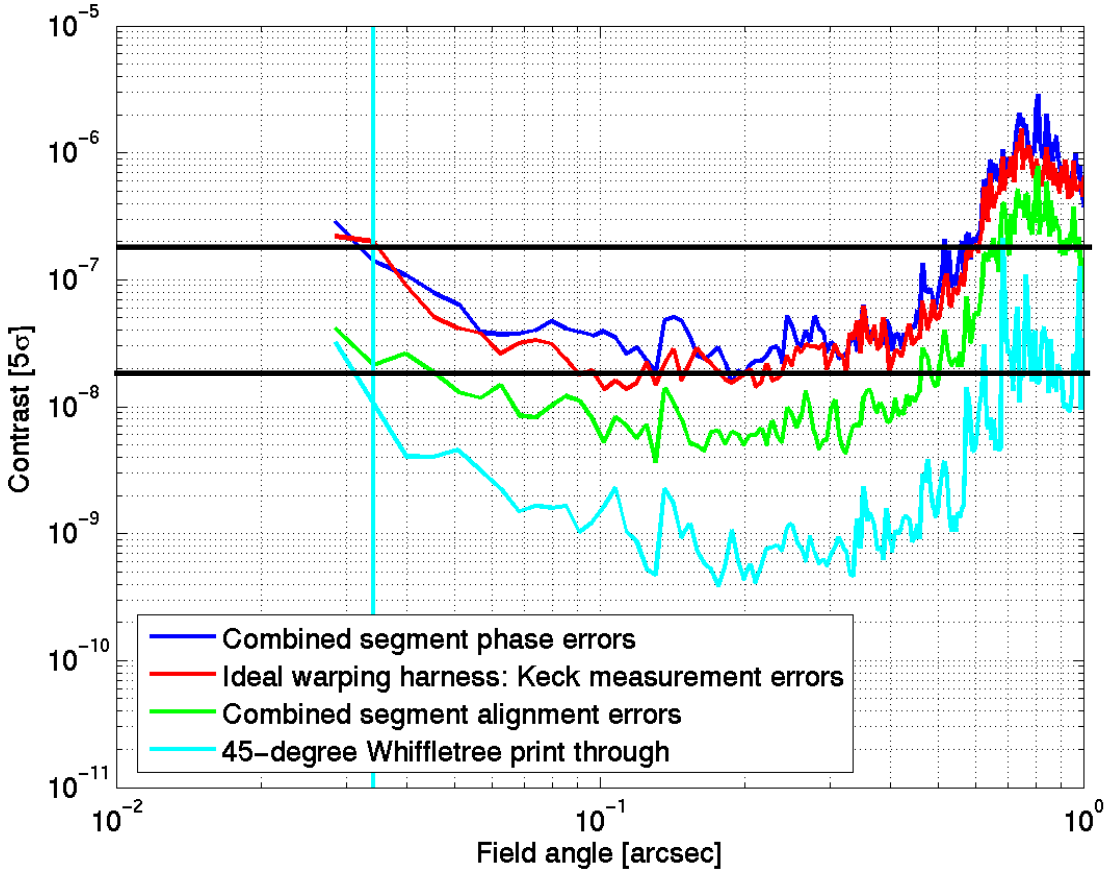
- RMS: 9.1 nm
- P-V: 199 nm

Contrast From Segment Alignment Errors



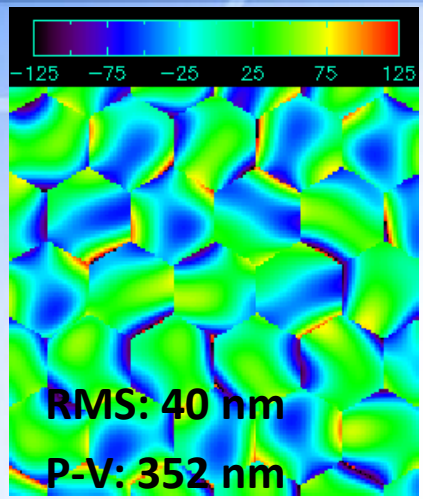
- Segment piston and residual tip/tilt errors are about equal in magnitude

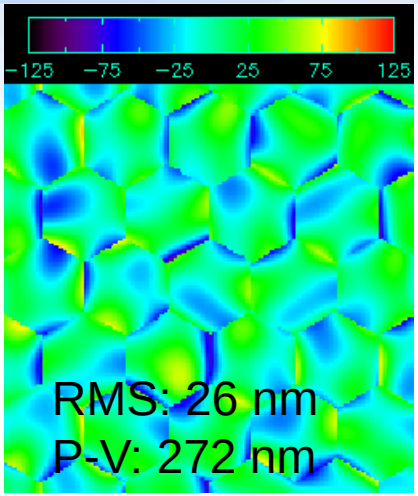
Contrast From All M1 Phase Errors

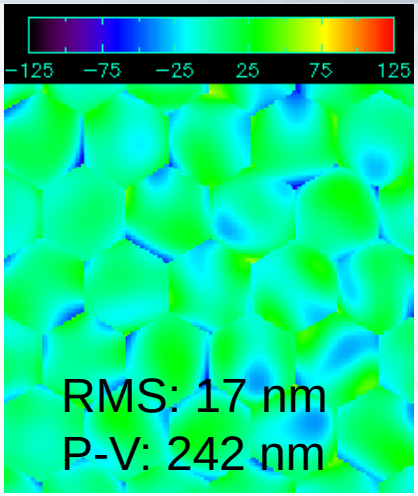


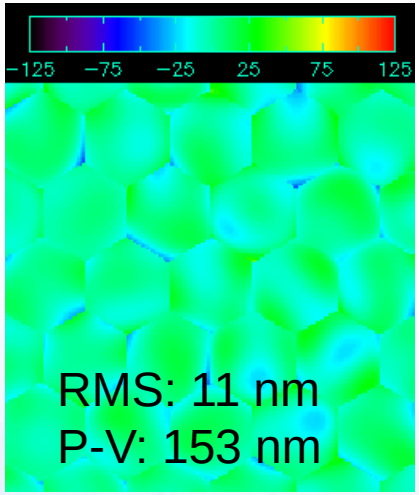
- Phase errors are dominated by residual segment aberrations
- Contrast is:
  - 1.4×10^{-7} at $3\lambda/D$
  - 5.6×10^{-8} from 3 to 10 to λ/D

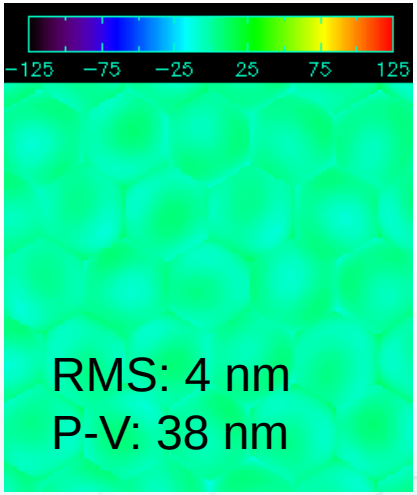
Various Segment Aberrations





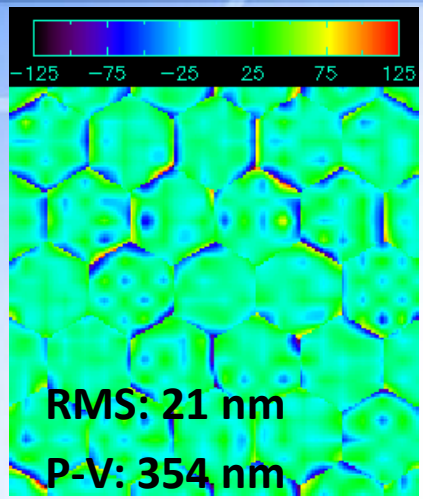


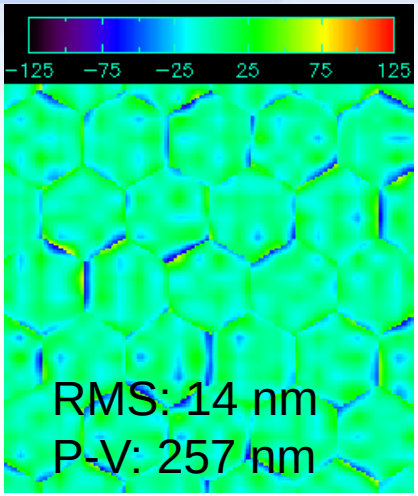


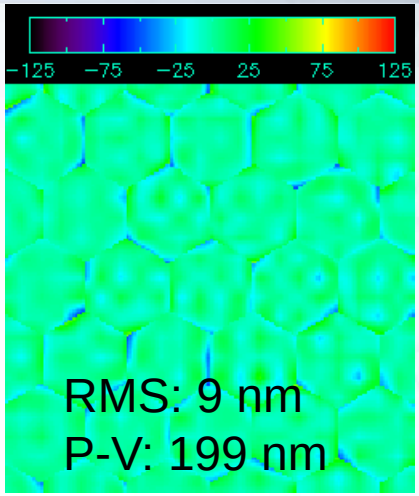


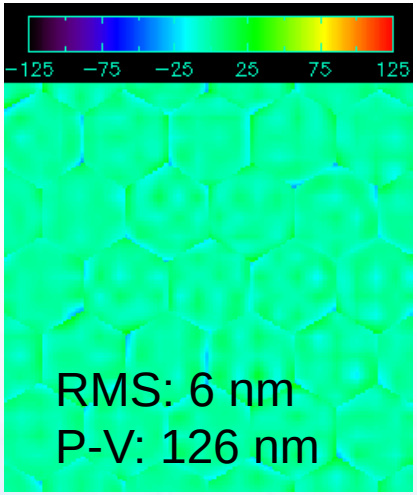
TMT AO Corrected Segment Aberrations

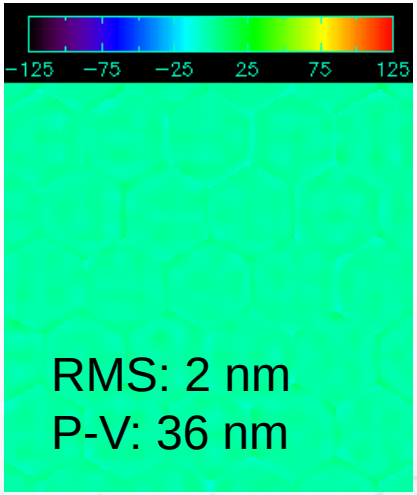
Thirty Meter Telescope



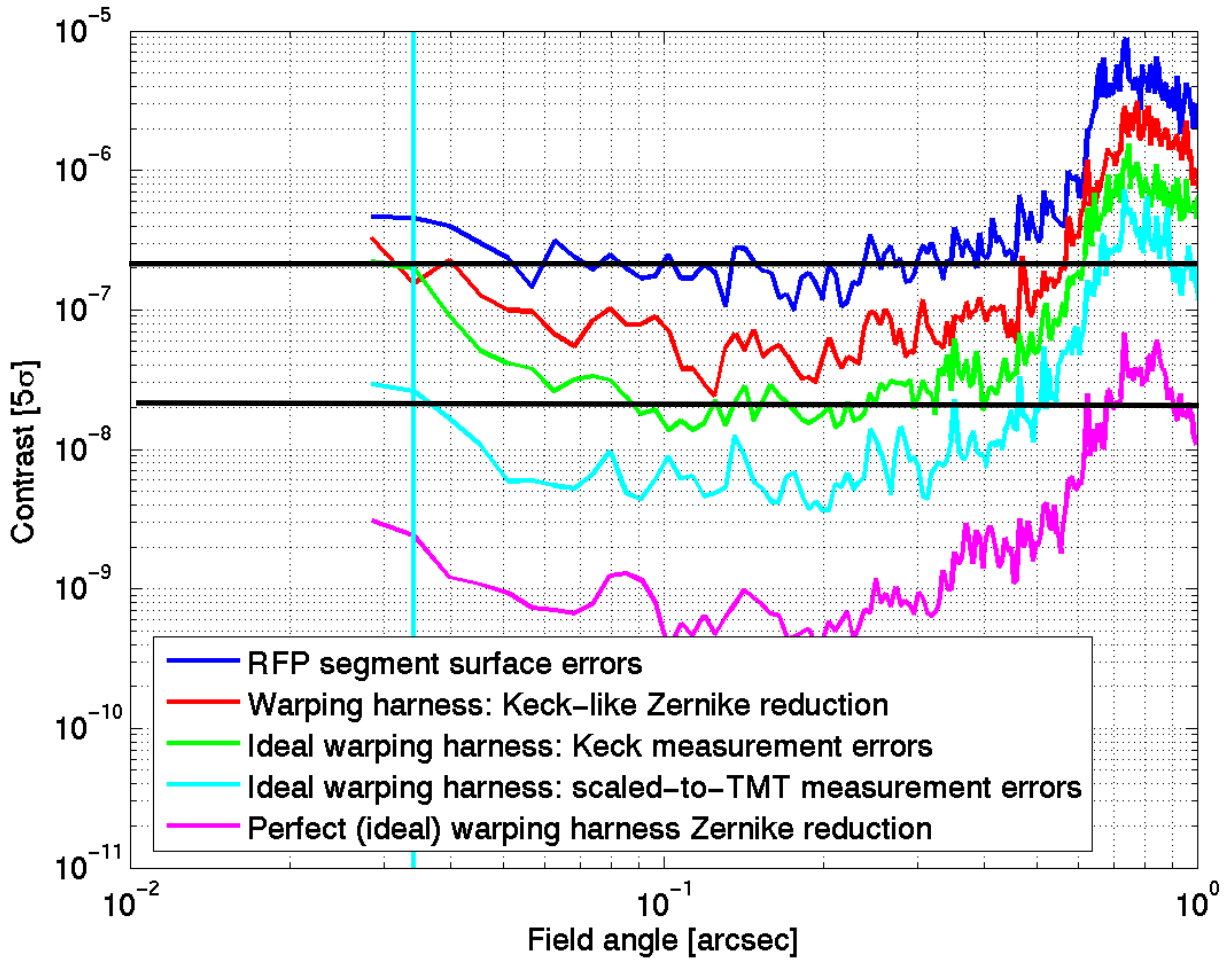








Contrast Versus Segment Aberrations Assumptions



Summary of Impact of Telescope Aberrations

- The telescope alignment errors are not a significant source of error
- Residual segment aberrations are a concern
- The current TMT estimates need to be updated using the latest:
  - Diffraction suppression systems
  - Updated predictions of telescope aberrations
- There are now several papers that calculate the impact on contrast from segment alignment and residual figure errors:

Acknowledgements

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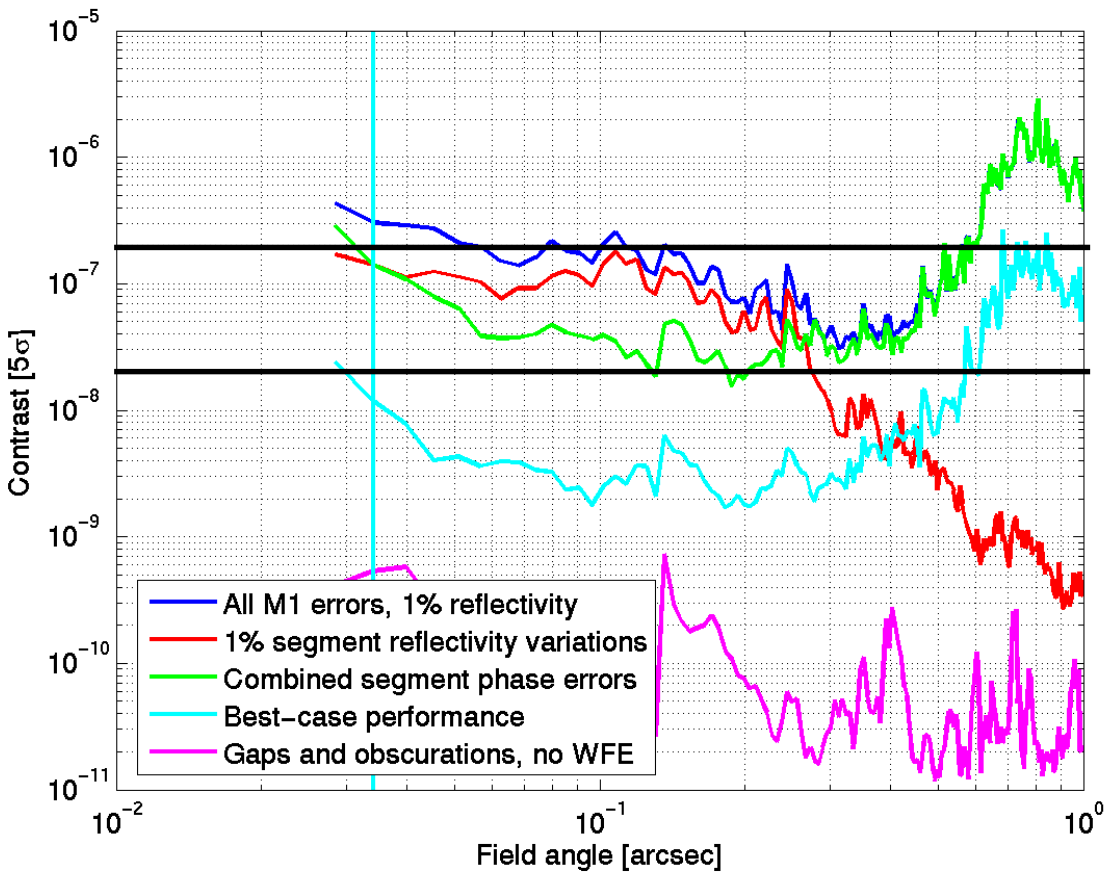
This work was supported as well by the Gordon and Betty Moore Foundation, the Canada Foundation for Innovation, the Ontario Ministry of Research and Innovation, the National Research Council of Canada, the Natural Sciences and Engineering Research Council of Canada, the British Columbia Knowledge Development Fund, the Association of Universities for Research in Astronomy (AURA) and the U.S. National Science Foundation.

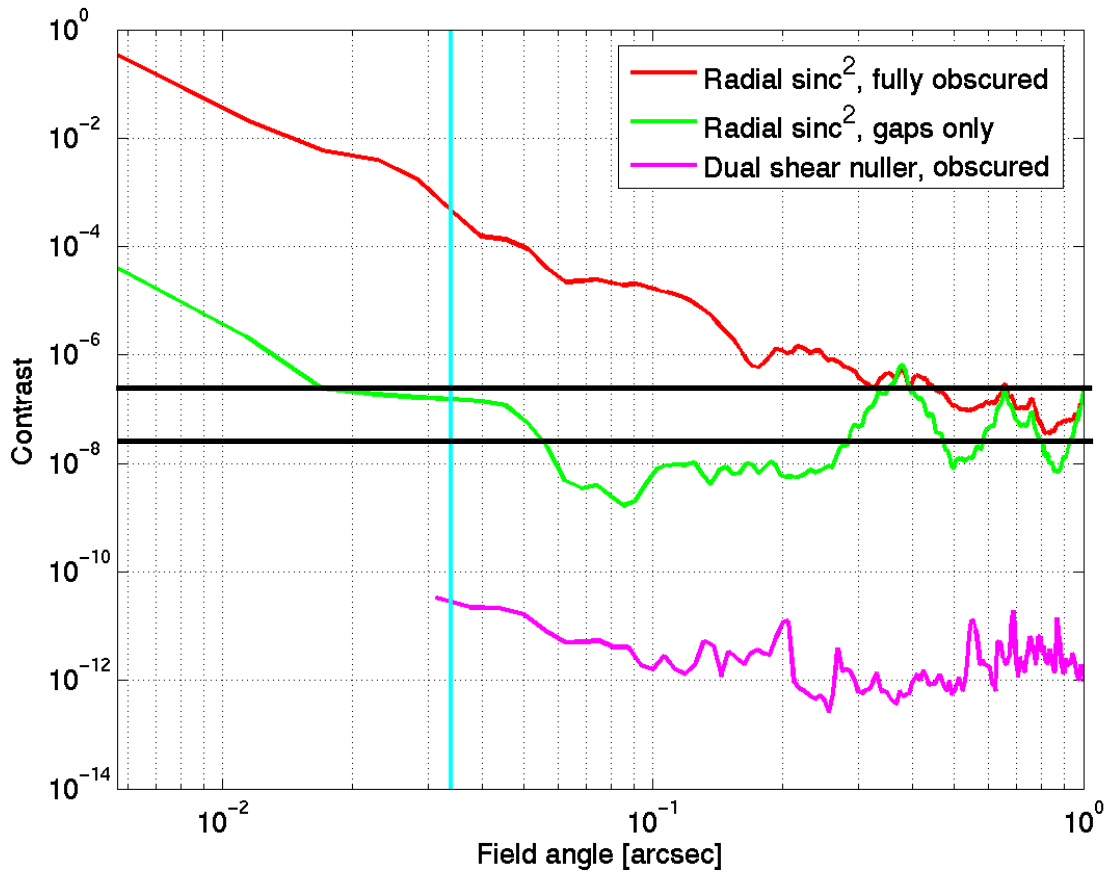
Backups

Contrast From All M1 Errors



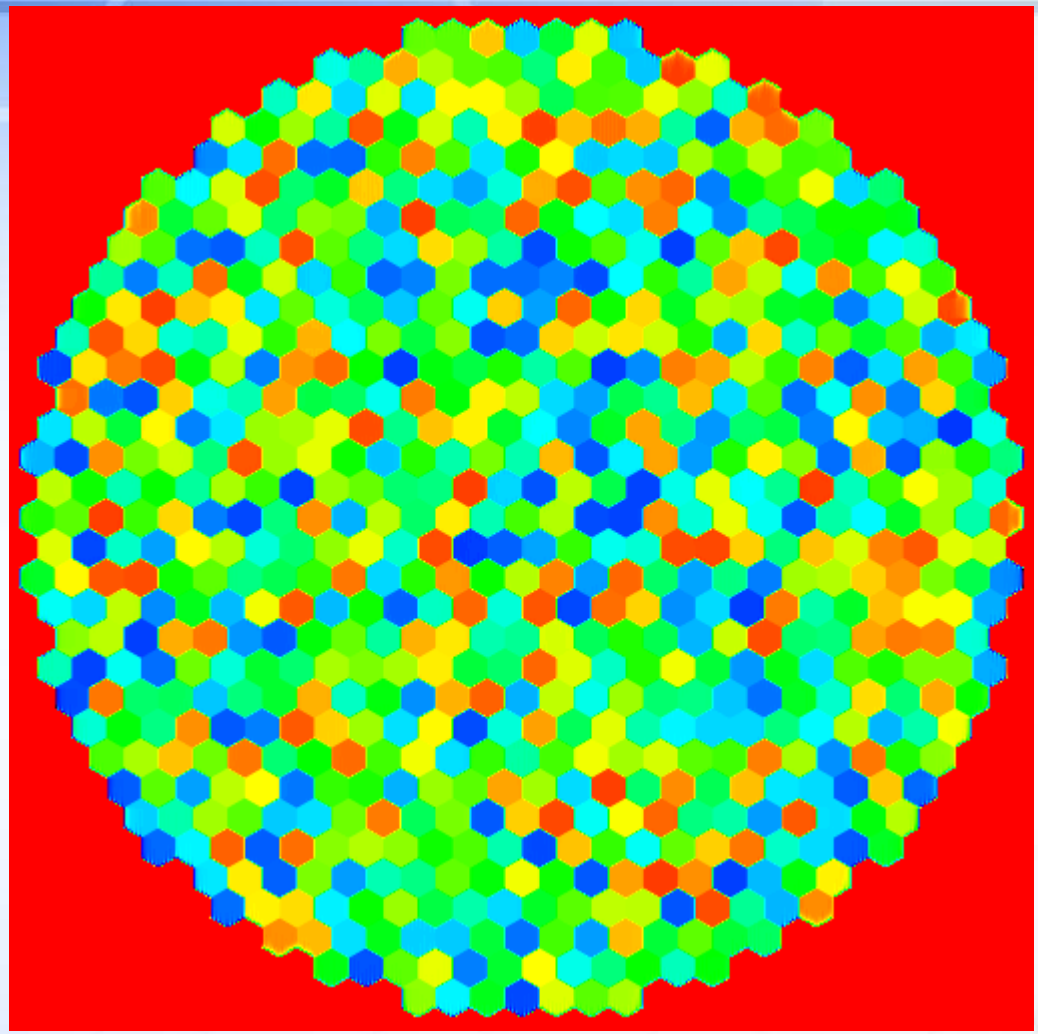
- Amplitude errors dominate and will be controlled
- Segment aberrations dominant error term
- Contrast is:
  - 1.4×10^{-7} at $3\lambda/D$
  - 5.6×10^{-8} from 3 to 10 to λ/D
- If WH performed at theoretical limits the telescope would not impact achievable contrast
  - 1.0×10^{-8} at $3\lambda/D$
  - 6.6×10^{-9} from 3 to 10 to λ/D

Contrast from Segmentation and Obscuration of Pupil



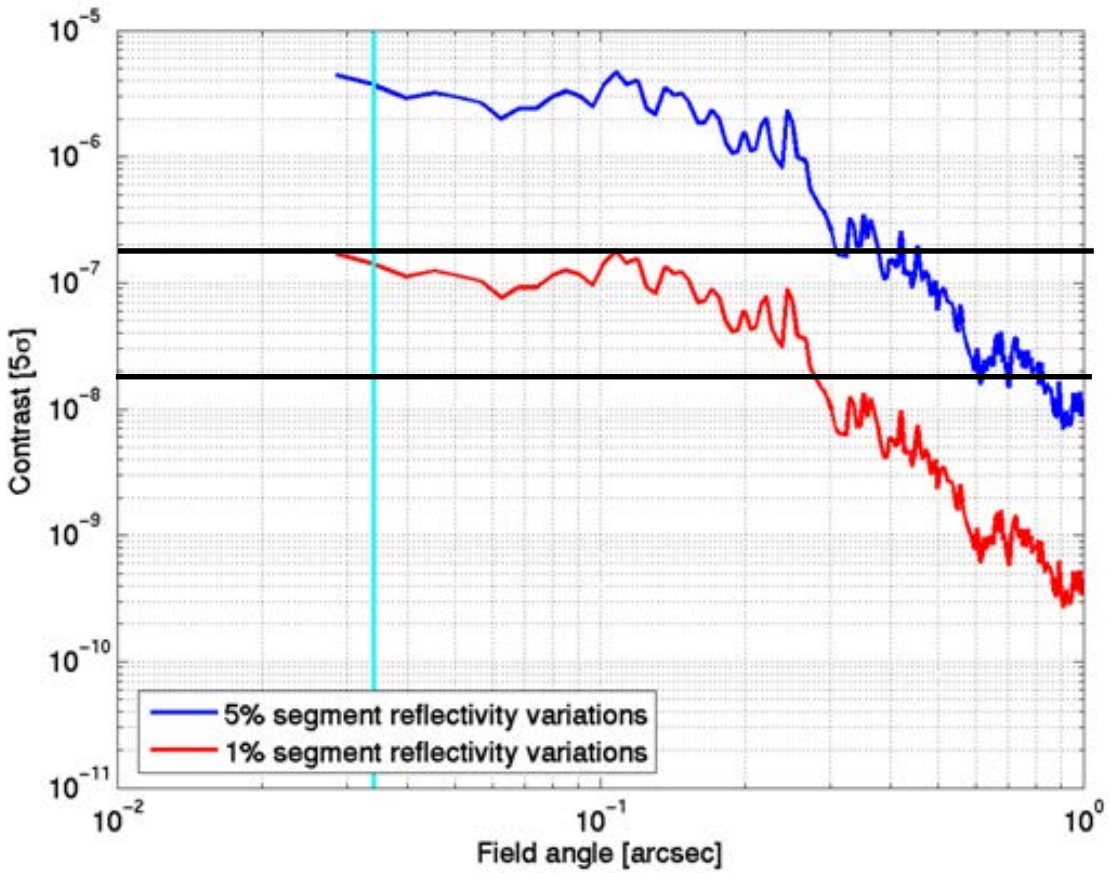
- Nuller exceeds contrast goals at all field angles

Contrast From Segment Reflectivity Variations



- TMT pupil with 1% segment reflectivity variations

Contrast From Segment Reflectivity Variations



- 1% segment reflectivity variations just meets requirement
- Contrast scales as amplitude error squared
- Will need to control amplitude effects unless reflectivity variation is ~0.3%
- Pupil reflectivity variations can be controlled by a 2nd DM not conjugate to a pupil

Summary of Shack-Hartmann Phasing

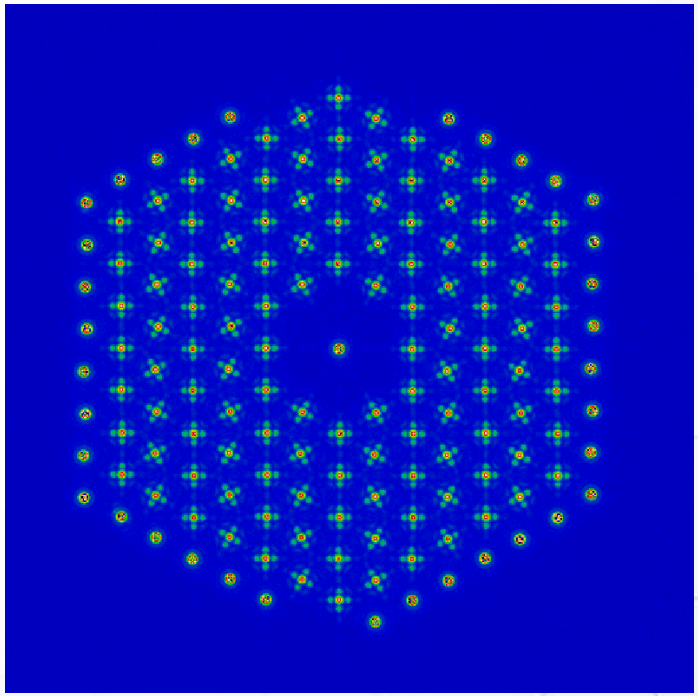
- "Shack-Hartmann" phasing is routinely used for phasing of segmented telescopes
- Has a capture range that can exceed $\pm 30\ \mu m$
- Has an accuracy to better than 6 nm RMS
- Can work with both atmospheric and lab turbulence
- Is not sensitive to global aberrations
- Can be combined with a "normal" Shack-Hartmann camera
- Can support coherence length or artificial wavelength phasing

Phasing and Shack-Hartmann Cameras Have Somewhat Different Requirements

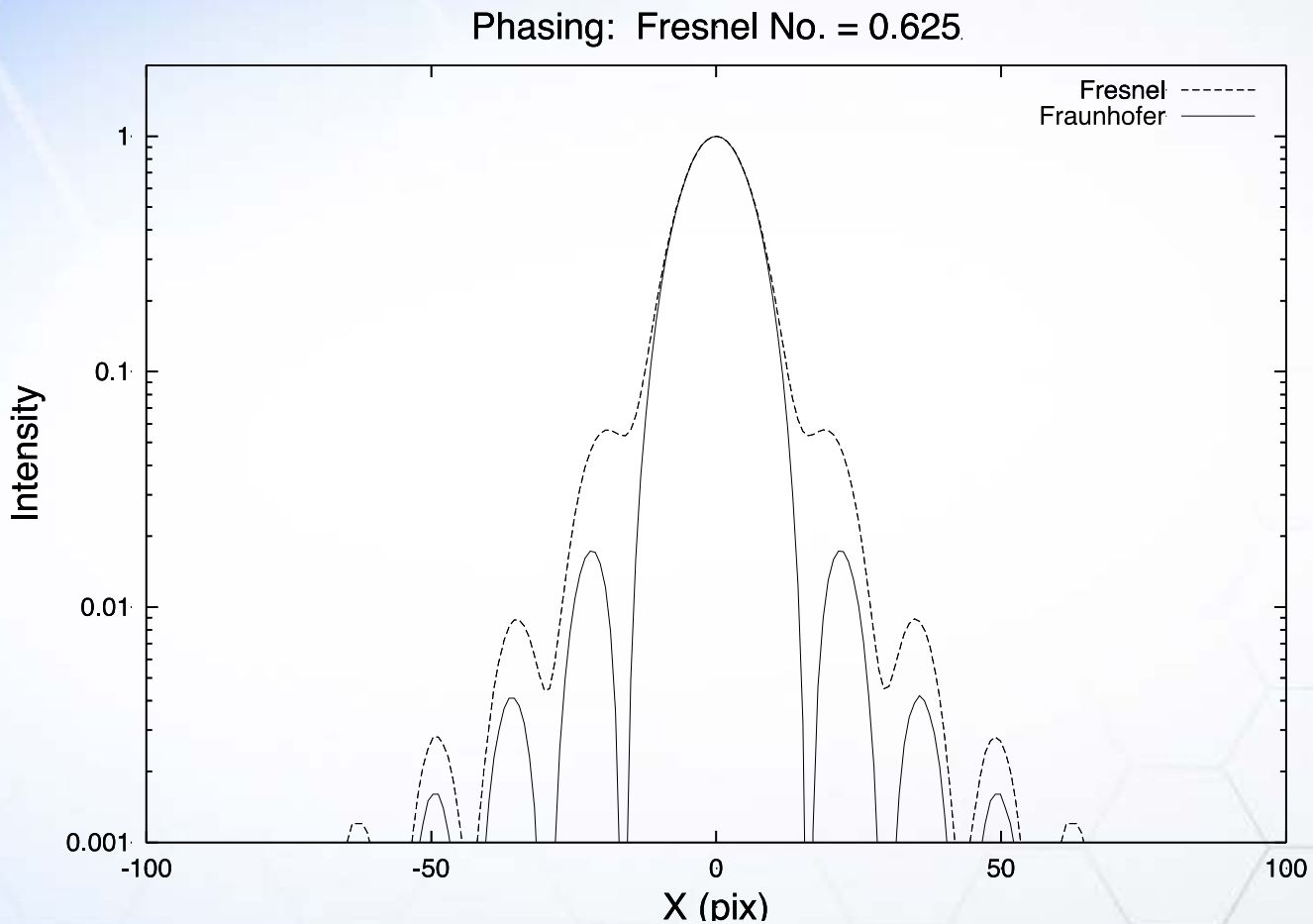
- Phasing requires a method to adjust the pupil location
  - Mask/Lenslet array should be on a stage
  - A piece of glass in the collimated beam that can be tilted
  - Accuracy is ~5% of a subaperture diameter
- The phasing camera re-imaged pupil must be of sufficient optical quality
- Focal plane plate scale:
  - Normal phasing: ~2 times Nyquist sampled images
  - Broadband phasing: ~4 times Nyquist sampled images

Keck Segment Phasing

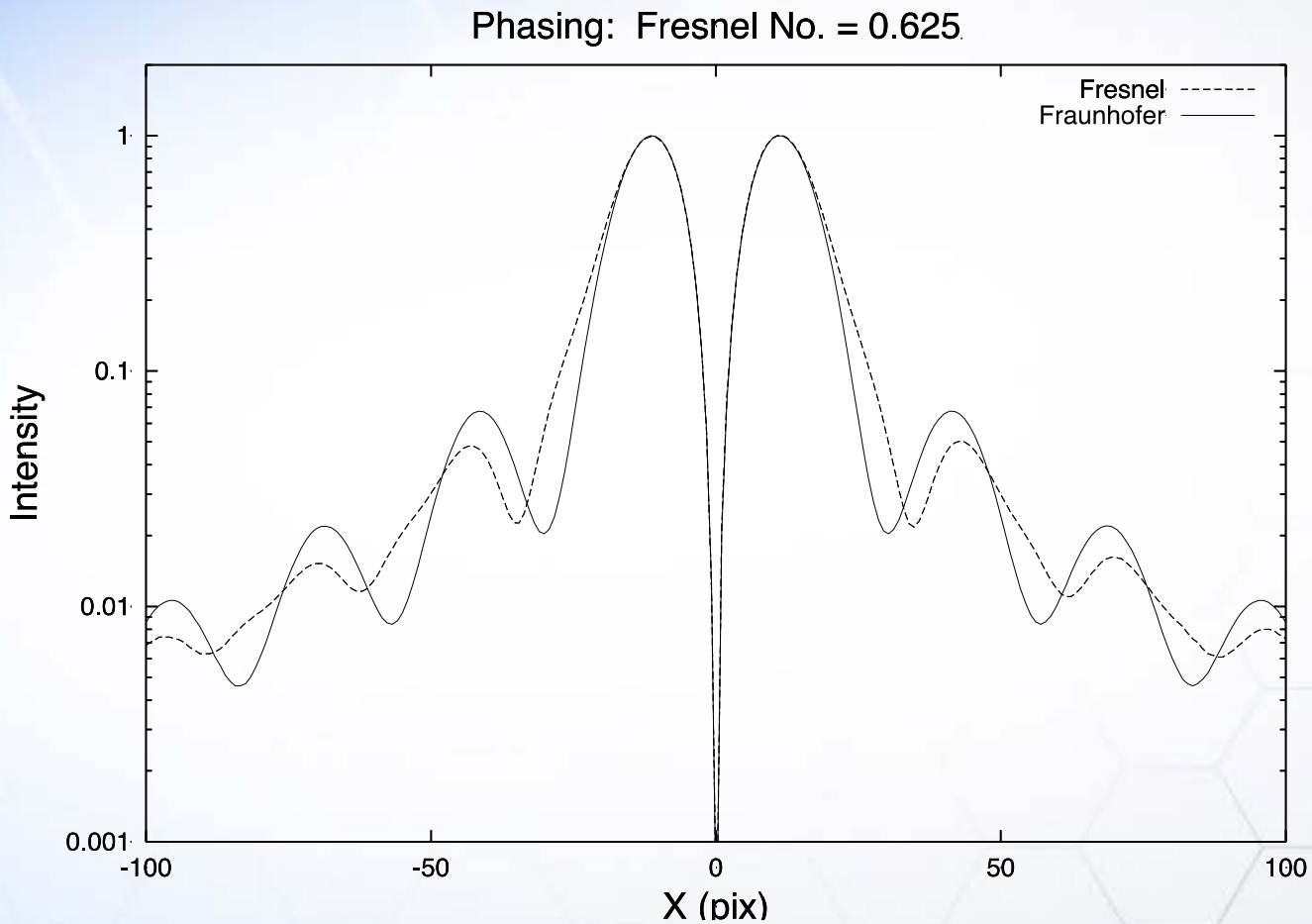
- Optic: Array of micro-prisms
- Wavelength: 611 to 891 nm
- Star Mag: V = 4 to 8
- Capture Range:
  - BB +/- 30 microns
  - NB +/- 200 nm
- Accuracy:
  - BB +/- 30 nm
  - NB +/- 6 nm



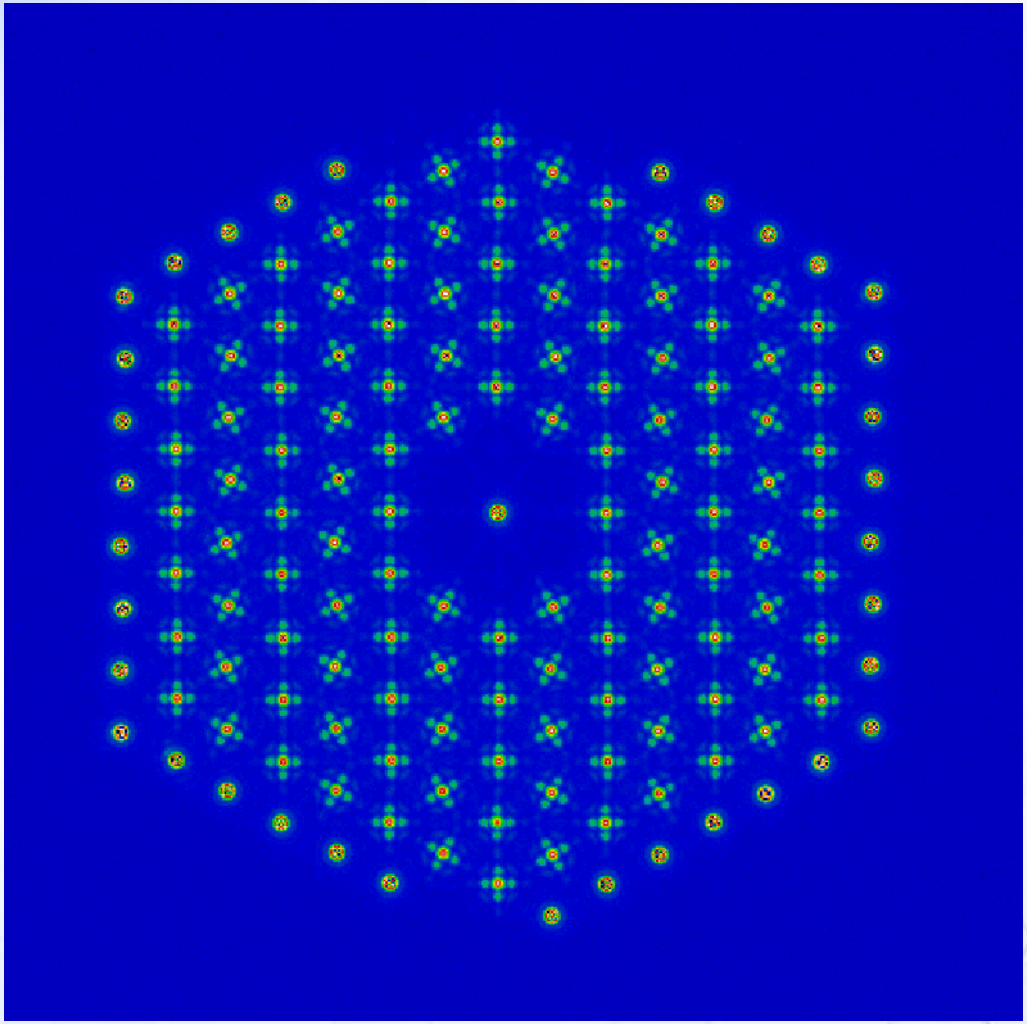
Fresnel vs. Fraunhofer: In-Phase Segments



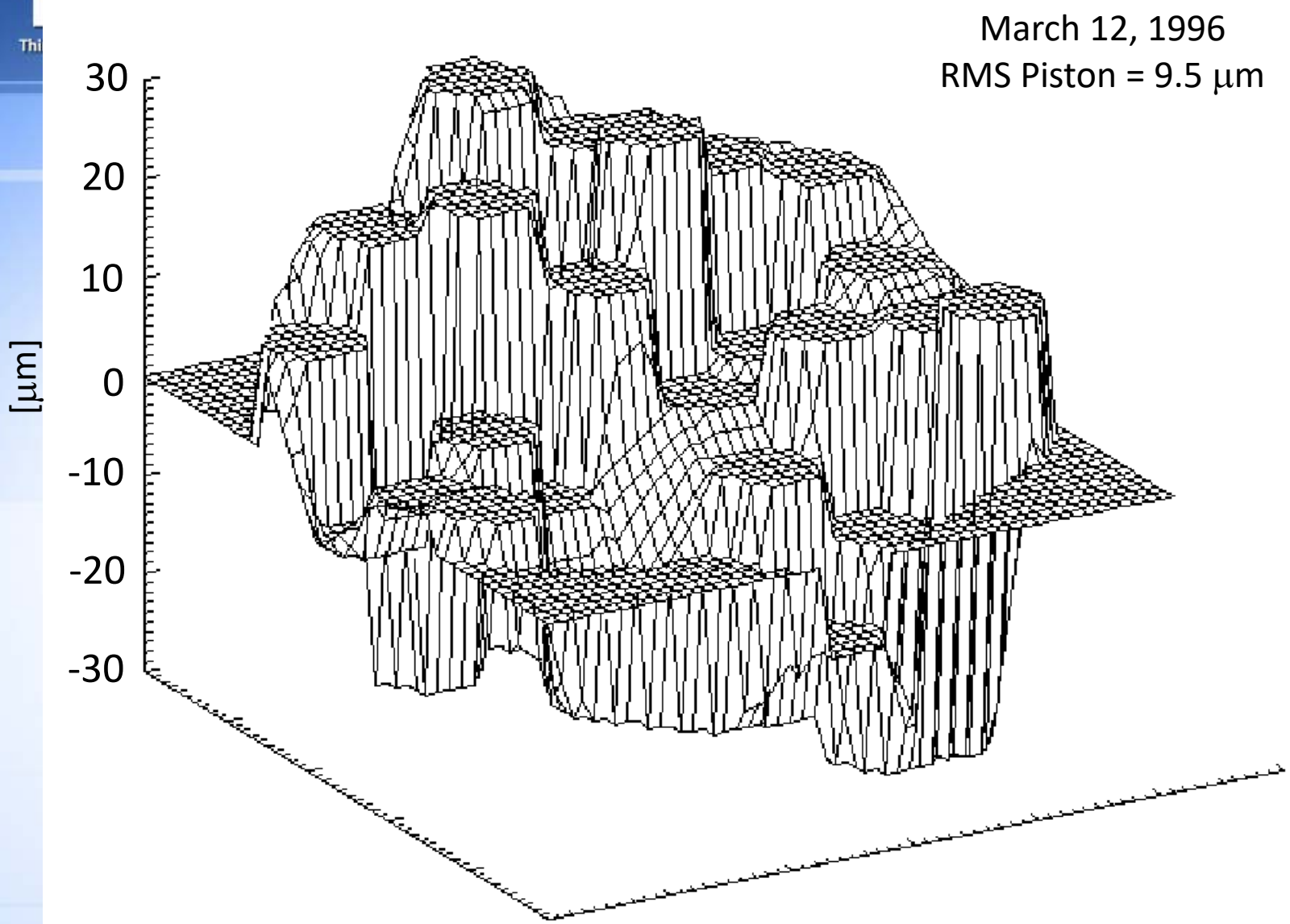
Fresnel vs. Fraunhofer: Out-of-Phase Segments



Phasing Reference Beam

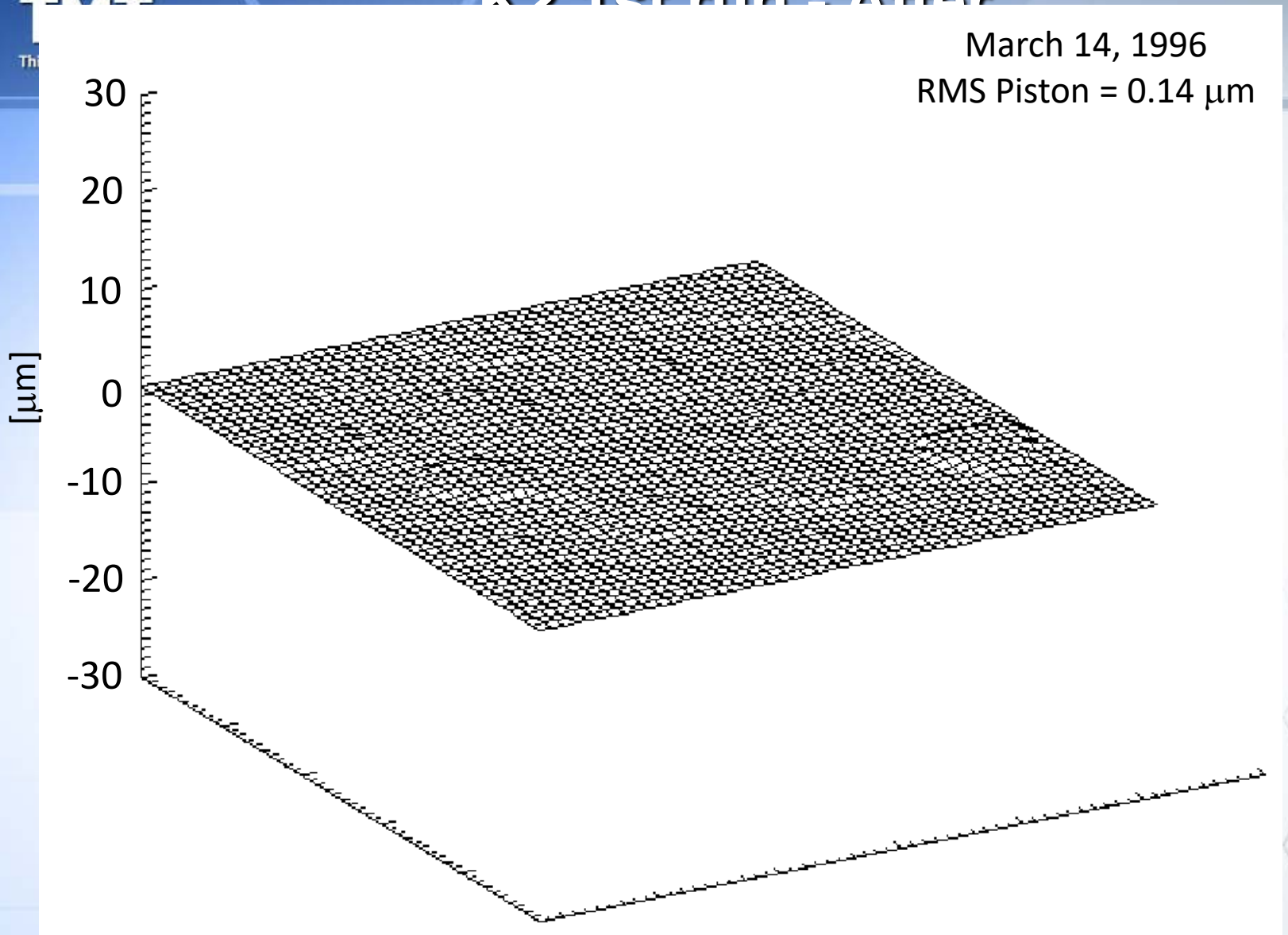


Primary Mirror Phase Error First Light (Keck II)



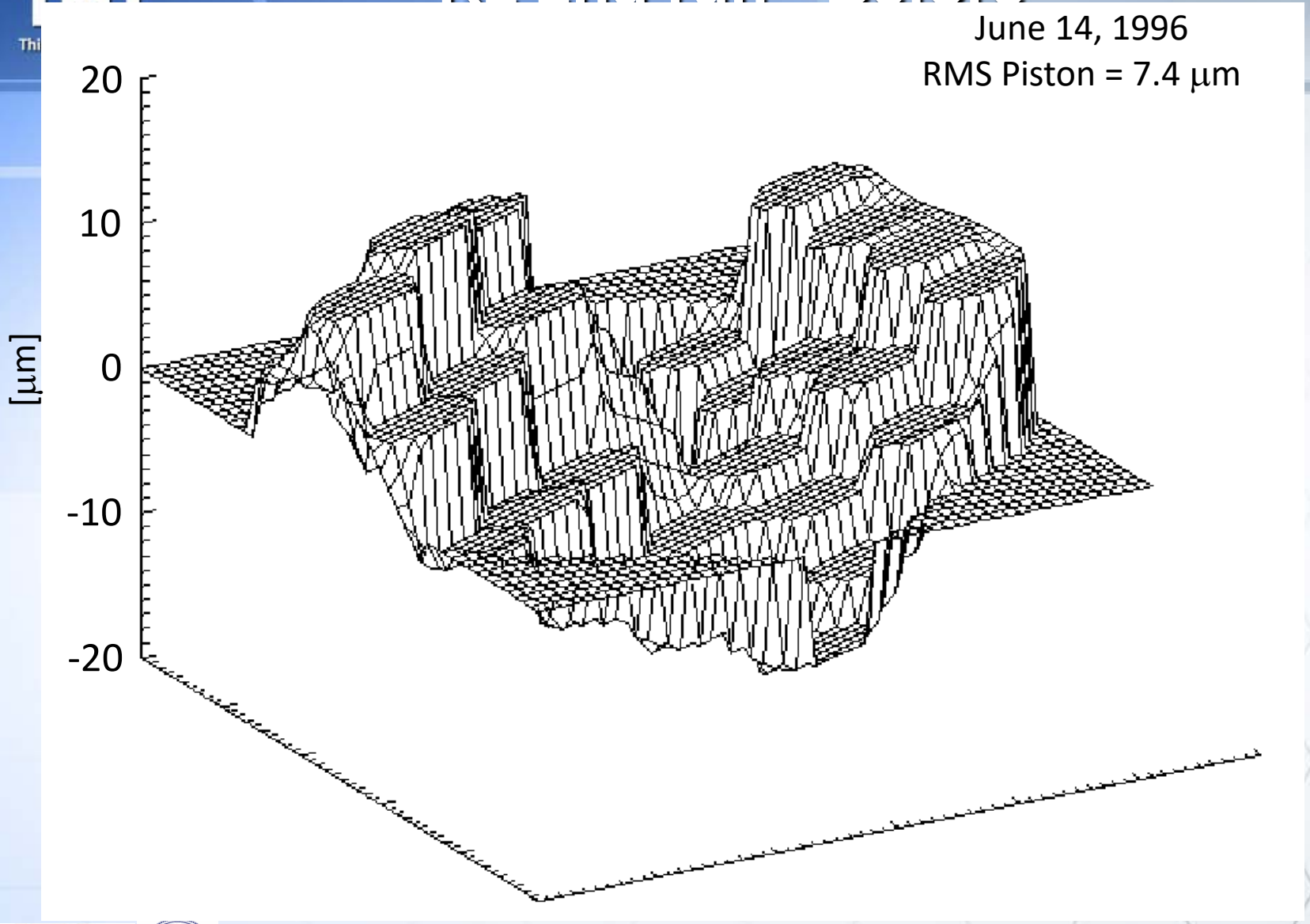
Primary Mirror After Broadband Phasing

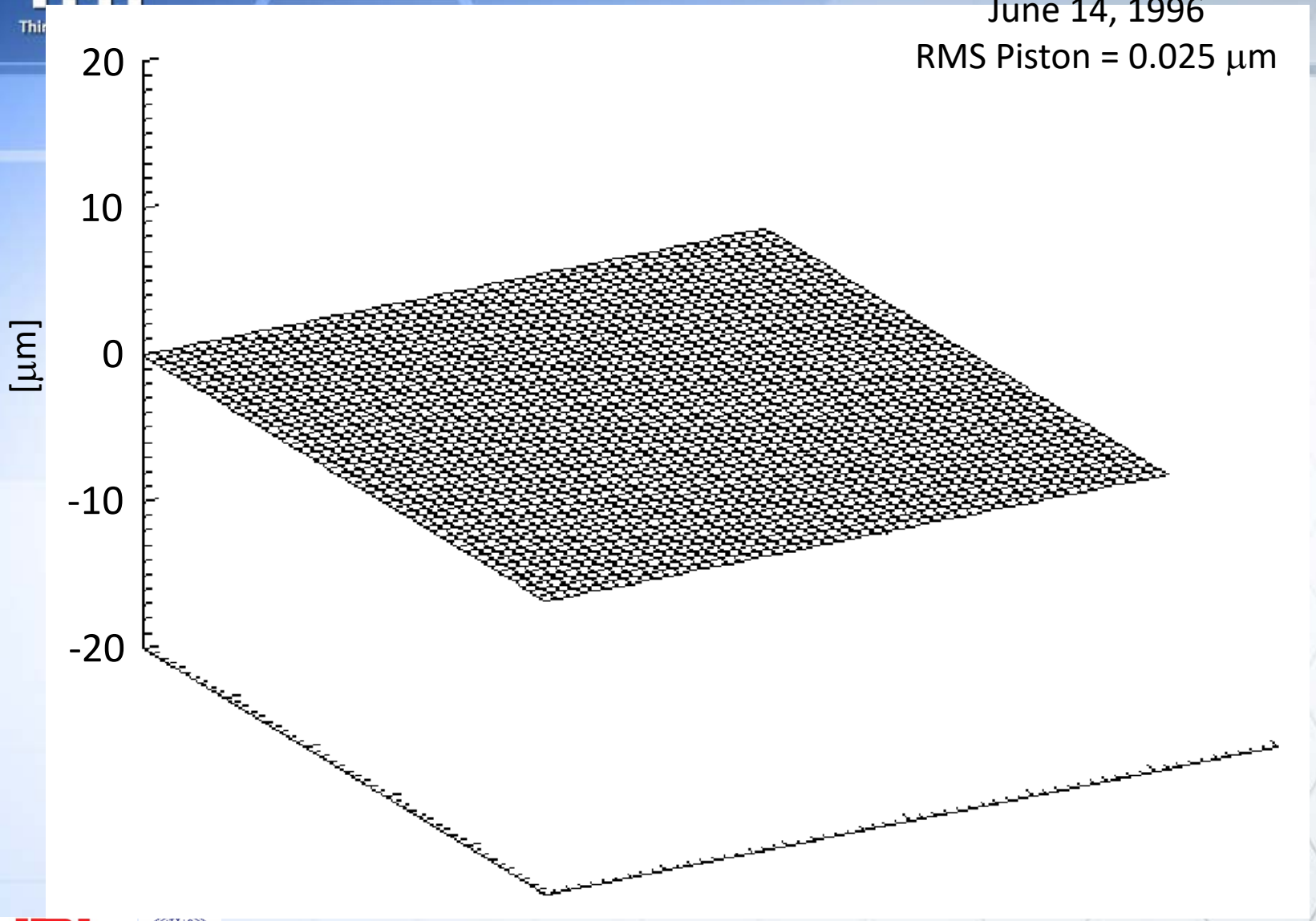
K2 1st run - After



Primary Mirror Phase Error First Light (Keck II)

K2 2nd run - Before



Primary Mirror After Phasing

K2 2nd run - After